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Virtual Reality
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ORIGINAL ARTICLE

Haptic modules for palpatory diagnosis training of medical students

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Abstract We have developed and evaluated a novel tool based on haptics and virtual reality technology for augmenting the teaching of palpatory diagnosis. This novel tool can act as an automated expert and an animated textbook to illuminate palpatory diagnosis concepts by touch on a laptop PC and by using affordable haptic interfaces that can be housed in a medical student resource library. It can be used for unlimited student practice for improving skills from Osteopathic Manipulative Medicine laboratory and also as a repeatable and objective measure of palpatory skill to track student progress. The system was evaluated by 22 osteopathic medical students (16 first- and 6 second-year). The majority of the participating students (>90.9 %) thought that future practice with the system may help them develop their palpatory skills. The majority (>77.3 %) of the students also thought that the instructions on the module screens were clear. When the students were asked about the user interface, most of the students (>86.4 %) responded that it was clear and easy to interpret. Evaluation results also showed that when the students were asked whether they would like to use the modules in the future for training at least 90.9 % of them answered "Yes" or "Maybe." The achievement of purpose ratings for individual modules changed between 6.27 and 8.82 on a 10-point scale. This project has the potential to be extended from osteopathic medicine to allopathic medicine, veterinary medicine, physical therapy, massage therapy, and chiropractic schools.

Keywords Haptic modules · Haptic medical simulation · Medical education · Osteopathic medicine · Palpatory diagnosis

1 Introduction

Palpation, an economical and effective first line of medical diagnosis used in many fields of healthcare, plays an important role in osteopathic, allopathic, and veterinary medicine. It is fast and inexpensive, but limited resources, that is, lack of real-life patients with a variety of problems and a lack of expert teachers, make training of professionals in these areas difficult. For instance, the training of osteopathic medical students on palpation methods is usually performed in laboratories where they work on each other. These settings do not provide the typical population (age and physical condition) that these students will diagnose and/or treat. Therefore, we developed the Virtual Haptic Back (VHB) as a training tool for medical students (Howell et al. 2005, 2006, 2008a, b). The VHB is a simulation of contours and tissue textures of a human back that is presented graphically and haptically. Students use haptic devices to feel the VHB and identify dysfunctional regions. A dysfunctional region is simulated as increased stiffness compared to the background stiffness of the palpable portion of the entire back.

The VHB is the only human back simulation that is actively being used in palpation training of osteopathic medical students. Burdea et al. (1999) developed a virtual reality-based simulator prototype for the diagnosis of

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prostate cancer using the PHANToM haptic interface. An earlier tumor palpation virtual reality simulation was developed by Langrana (1997). Dinsmore et al. (1997) created a virtual reality training simulation for detection of subsurface tumors (hard regions underneath the surface of virtual livers) using the Rutgers Master II force feedback system. E-Pelvis is another example of a palpation simulator (Pugh et al. 2001; Pugh and Youngblood 2002). It is an electronic mannequin that enables users to see on a computer screen where in the pelvis they touch during training and the pressure they apply to those touch points. The availability of objective performance data (the applied pressure, number of times a critical point with a sensor is touched) also makes it an assessment tool. There are also palpation simulators in veterinary medicine. The bovine rectal palpation simulator is used to teach veterinary students to identify fertility problems and diagnose pregnancy (Baillie et al. 2005). Another example is the simulator developed for feline abdominal palpation training (Parkes et al. 2009). A survey of palpation simulators, as classified into three types (physical model based, virtual reality-based, and hybrid simulators), can be found in (Zhang et al. 2009).

We are developing the haptic modules described in the current article to reinforce palpatory diagnosis principles learned in osteopathic manipulative medicine (OMM) and palpatory laboratories, in a more portable and affordable manner than the existing VHB.

The modules were developed and programed in one umbrella program to be used on a laptop PC. They were designed in such a way that each module targets improving a certain aspect of palpation and introducing some of the hardest clinical concepts to comprehend and master toward becoming skilled osteopathic manipulators. A mastery algorithm was developed and programed for all modules, where the computer automatically adjusts the difficulty level based on trainee performance and automatically assesses their mastery level in each evaluation session. A database automatically stores training and evaluation data from any number of subjects, including both objective performance data and subjective questionnaire responses. The training on the modules is based on comparison of physical properties such as stiffness, motion, and force magnitude between two objects/directions. As a part of the learning process, the clinical relevance and goal of each module are presented to the user before he/she starts training on a particular module. Upon an incorrect answer, users are given the opportunity to feel the correct response until they are comfortable to proceed to a new trial.

In this article, we present the development efforts and discuss the evaluation results for the six haptic modules: bump height, stiffness discrimination, fascial drag, ropey, pitting edema, and bump location.

2 System description

2.1 Haptic interface

Haptic interfaces provide the sense of force and touch to users from virtual simulations on the computer. For our purposes, we need users to interact with the virtual environment using their fingers rather than the whole hand or the forearm. There are haptic devices which are commercially available (Phantom® Omni, Phantom® 3.0, SensAble.com, 2010; CyberGlove™, Kessler et al. 1995) or being used in research labs (DigiHaptic, Casiez et al. 2003; SPIDAR-8, Kohno et al. 2001) that meet this requirement. The haptic interface used in this project, the Omni® (Fig. 1a) from SensAble Technologies, Inc., was modified in order to provide finger interaction (Fig. 1b) rather than using the provided pen-like stylus (Fig. 1a).

The Omni® was chosen because of its commercial availability, relatively low cost, and our years of experience using its OpenHaptics software development kit.

This gimbaled modification of the Omni® haptic interface enables users to interact with the virtual environment with the finger or thumb of choice as they would in a clinical situation. The design also includes a finger strap that can be adjusted to accommodate different finger sizes.

2.2 Virtual environment

The virtual environment for the modules was designed using the same functional elements in order to ease the transition from one module to the other. The users are required to navigate and interact in a three-dimensional space by means of the haptic interface after they sign in using the main menu. The main menu for the haptic modules is a dialog box and serves as the entrance to the system. Using the main menu, users can (1) Create a user name and a password before they start their training, (2) Retrieve their user name/password in case they forgot these items, (3) Select the module with which they would like to train, and (4) View their progress report. Users are required to sign in to be able to access the available modules which are activated upon entering a correct user name and corresponding password. This unique user name is necessary to store individual user data in the database and, therefore, to keep track of users' progress with practice.

The screen layout (Fig. 2), in terms of functionality, is the same for all of the modules and consists of several elements (the bump location module is shown). A user feedback status box presents information on the current level, number of correct responses, and whether the last given response was correct or incorrect. Another box includes the set of instructions for each module. The

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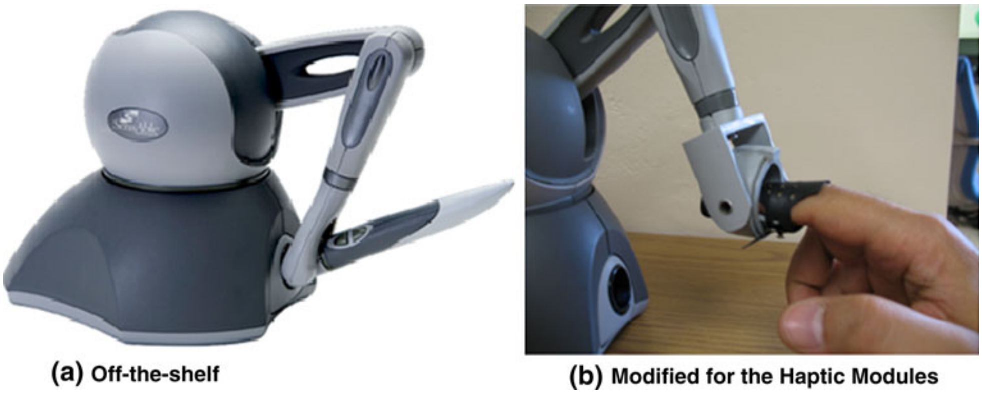


(a) Off-the-shelf

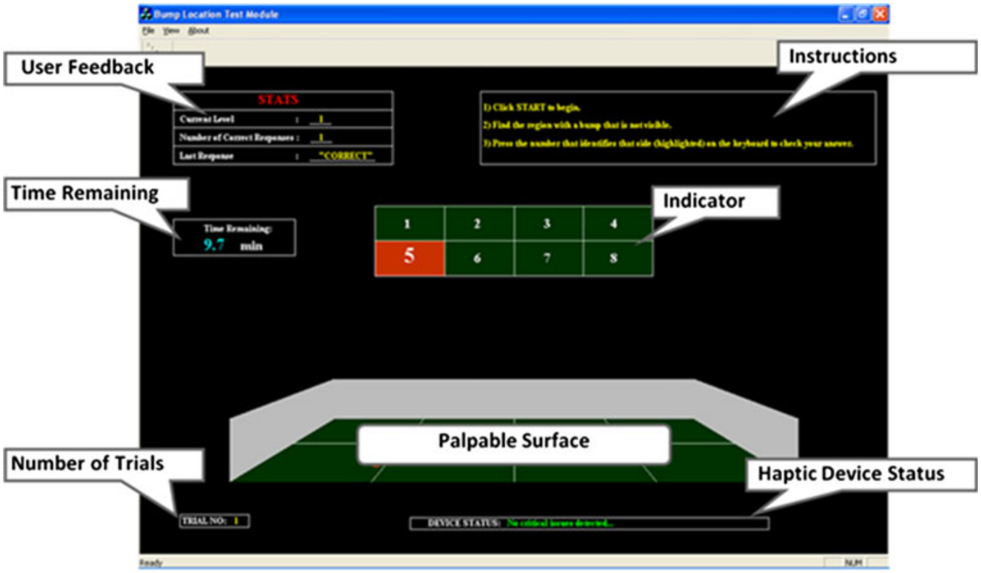
(b) Modified for the Haptic Modules

Fig. 1 Omni$^{®}$ Haptic Interface (SensAble Technologies, Inc.). **a** Off-the-shelf. **b** Modified for the haptic modules

indicator in the middle of the screen shows which button the users will press on the keyboard (highlighted) to respond to the current testing task at hand. Its shape and function varies considerably between the modules depending on the skill tested. The palpable surface changes according to the specific goal of that particular module. This is the main testing area and the only region where the users have force feedback. The haptic device status is also displayed to the users to warn them in case they apply a force that exceeds the manufacturer's recommended maximum force. The position of the users' fingers inside the virtual environment is displayed using a haptic cursor. The haptic cursor can be chosen by users to be a virtual right/left hand or a small sphere indicating the fingertip (not shown—see later figures starting with Fig. 3, showing the right-handed option). The orientation of the virtual hand can be adjusted any time during a training session. The remaining time for that session and the number of trials are also displayed as a part of the screen layout.

2.3 Mastery algorithm

The purpose of the mastery algorithm is to automatically identify the best level attained by each subject in a testing session. The best level is the most subtle (difficult) level of palpatory skill the subject achieves. For all modules, 11 levels of skill are implemented, with 1 being the easiest and 11 being the most difficult. Increasing levels is associated with better performance and decreasing levels with worse performance. The mastery algorithm for all of the haptics-augmented palpatory diagnosis modules is designed as follows: (1) Each subject is started at the easiest level for all modules; (2) The level is increased automatically by the program when the user either gets three correct answers in a row or six correct answers out of the last 10 responses; (3) The level is decreased automatically by the program when the user either gives 4 incorrect answers in a row or cannot get six correct answers out of the last 10 responses. This mastery algorithm was adapted from the VHB project (Howell et al. 2008c).



STATS

Current Level : 1

Number of Correct Responses : 1

Last Response : "CORRECT"

1) Click START to begin.

2) Find the region with a bump that is not visible.

3) Press the number that identifies that side (highlighted) on the keyboard to check your answer.

Time Remaining: 9.7 min

TRIAL NO: 1

DEVICE STATUS: No critical issues detected...

Fig. 2 Sample screen layout for the haptic modules

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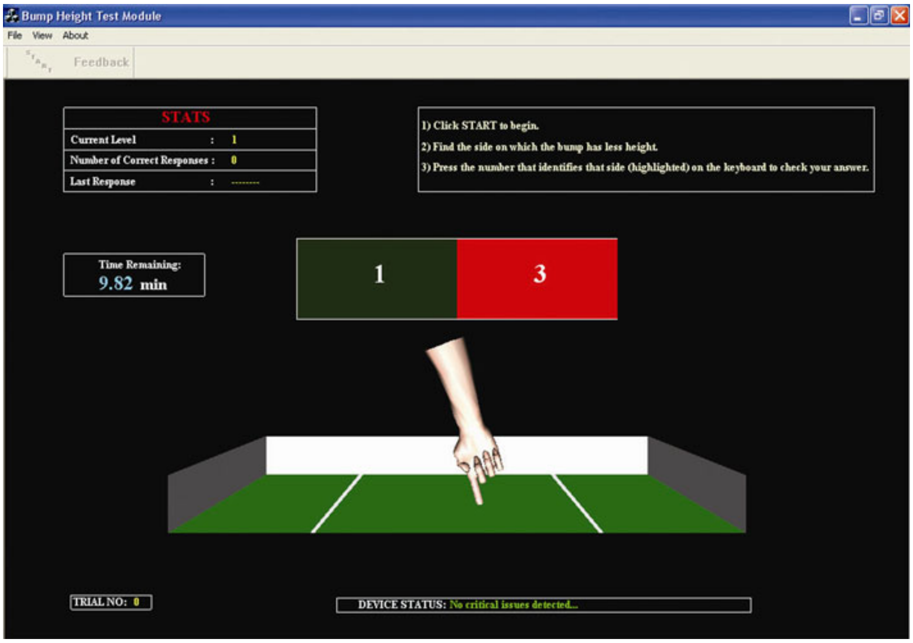

STATS

Current Level : 1

Number of Correct Responses : 0

Last Response : --------

1) Click START to begin.

2) Find the side on which the bump has less height.

3) Press the number that identifies that side (highlighted) on the keyboard to check your answer.

Time Remaining: 9.82 min

TRIAL NO: 0

DEVICE STATUS: No critical issues detected...

Fig. 3 Bump Height Haptic Module screen shot

The current session for any module is terminated after 3 level reversals (a method of termination used in psychophysics experiments, e.g. Karadogan et al. 2010) or after reaching the overall 10-min time limit, whichever comes first. A reversal is a change in level in the opposite direction, namely when a previous increase (or decrease) in the level is followed by a decrease (or increase) in the level. The last successful level within these constraints is defined to be the subject's achievement for that particular test and is termed the subject's "Mastery Level." Once the current session is completed, users can start another session of the same module or any other module using the main menu as long as they remain signed into the system.

2.4 User performance reports

In addition to the instant feedback users receive during training on the haptic modules as to correct and incorrect answers, users can also view their performance reports. The purpose of these reports is to keep track of the users' performance over time and allow them to see their standing with repeated training. Users can see their reports any time, after they sign into the modules with their username and password, by clicking on a button on the main menu. Users are automatically provided with an MS Excel file with four graphs for better visual interpretation of their performance. The graphs included in the report show (1) the mastery level by session; (2) the accuracy (percentage of correct answers) by session; (3) the total time per level by session; and (4) the average trial time per level by session. These performance measures for a steady improvement should result in higher mastery level and accuracy with decreased average time over several practice sessions.

3 Haptic modules

We have developed six haptic modules for palpatory diagnosis activities for osteopathic training: bump height, stiffness discrimination, fascial drag, ropey, pitting edema, and bump location modules. These modules were designed to improve user skill and confidence in palpation by using a haptic interface that allows for immediate feedback and tracking of skill level. The following sections present the clinical relevance and underlying model of each of these modules in detail. The goal and clinical relevance for each module are displayed to the users before they start training on that particular module. The haptic modules development was accomplished iteratively in close consultation with expert palpators (OMM faculty and fellows).

3.1 Bump Height Haptic Module

Clinical relevance The asymmetry of patient anatomical structures may be identified via touch by comparing the position (height) using two fingers. Palpation of tissue asymmetry is an important skill in physical examination, orthopedic testing, and OMM. OMM trains osteopathic medical students to detect fine differences in tissue asymmetry to diagnose and treat somatic dysfunctions. Glossary of osteopathic terminology (ECOP 2006) defines somatic dysfunction as "Impaired or altered function of related components of the somatic (body framework) system: skeletal, arthrodial and myofascial structures, and their related vascular, lymphatic, and neural elements." In clinical practice, palpatory diagnostic testing includes evaluation of static landmark positional asymmetry in

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sagittal, coronal, and transverse planes (Degenhardt et al. 2005).

Model The purpose of this module is to train the palpatory diagnosis skill of distinguishing different patient tissue bump heights. Users quantitatively compare the height of two bumps, shown in Fig. 3, and identify the shorter one. As the difficulty level increases, the height difference between the bumps decreases. The height difference decreases down to a level (0.06 mm) which is slightly higher than the position resolution of the haptic interface (0.055 mm). Users can only feel the bumps during a trial unless they give an incorrect answer. In the case of an incorrect answer, users are allowed to see and feel the correct answer until they are ready to continue with the next trial.

As shown in Fig. 4, the contours of the bumps are drawn as ellipses that extend into the screen. The bumps are invisible during a trial, that is, the users must respond based solely on haptic feedback. An incorrect answer, however, reveals the bumps, enabling the user to compare the heights of the bumps by feeling and seeing the correct answer. Then, the user can proceed to the next trial by pressing the spacebar on the keyboard whenever he/she is ready. During this period, the timer is stopped in order not to rush the user to proceed to the next trial.

A smoothing region from the flat surface to the elliptic surfaces where the bumps are drawn is necessary. Otherwise, the slope of the surface that users feel would suddenly increase from zero (flat surface) to the slope of the elliptic surfaces which is relatively higher. These transition regions are defined by using a 2D Gaussian function:

$$f(x,y) = Ce^{-\left(\frac{(x-x_0)^2}{2\sigma_x^2}+\frac{(y-y_0)^2}{2\sigma_y^2}\right)} \tag{1}$$

where C is the amplitude of the Gaussian function, σ_x and σ_y define the spread of the curve, and (x_0, y_0) is the center of the curve on the xy plane when $\sigma_x = \sigma_y$ (Fig. 5a). The Gaussian function with different σ_x, σ_y values is used to create the transition regions (gradual increase of slope) on both sides of the elliptic surfaces (Fig. 5b) for the Bump Height Module.

3.2 Stiffness discrimination haptic module

Clinical relevance Changes in patient tissue may be in the form of contour changes, stiffness changes, or both. Clinically, tissue stiffness is associated with ischemic and fibrotic changes in a tissue associated with injury, chronic overuse, and/or repetitive stress. Tissue stiffness is used as a diagnostic tool in the indication of somatic dysfunction in OMM (DiGiovanna and Schiowitz 1991). This module helps the users increase their sensibility to stiffness discrimination.

Model The purpose of this module is to train the palpatory diagnosis skill of identifying stiffer tissue. As shown in Fig. 6, users identify the stiffer of two surfaces (top faces of the cylinders) by touch. Stiffness is the reciprocal of compliance.

As shown in Fig. 7 (front view), the palpable surfaces for stiffness discrimination are the top faces of two cylinders. One of the surfaces represents the standard stiffness which remains the same throughout a session. The stiffness of the remaining surface is less than the standard stiffness at all times. The stiffness difference between the surfaces decreases with increasing difficulty level in a training session. There is no height difference between the surfaces. The location of the cylinders is switched randomly throughout a session.

3.3 Fascial drag haptic module

Clinical relevance Compressed or twisted patient fascia is associated with biomechanical stress or strain in the musculoskeletal system. This may be caused by direct injury, sub-optimal biomechanical compensation, or decomposition of previous compensatory patterns over time. The change in tension of fascia may also be caused by different reasons such as abnormal muscle activity or change in the positions of bones or viscera (Cathie 1974). Fascial drag is utilized in both the diagnosis and treatment of somatic dysfunctions in OMM. Osteopathic medical students are trained to palpate fine degrees of fascial drag throughout all regions of the body. This is considered to be an advanced form of palpation that requires palpation exercises and practice.

The real-life implementations of training in the fascial drag module may be exemplified, for instance, by considering the situation where the skin on the back in lung conditions shows increased drag when examined with a light touch over the affected area. The amount of involvement may be realized by comparing this feel of increased resistance to healthy regions of the skin (Carter 1927).

Model The purpose of this module is to train the palpatory diagnosis skill of identifying the direction of maximum tension due to underlying fascia. As shown in

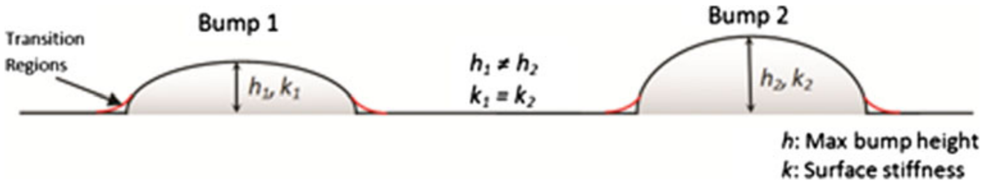

Fig. 4 Bump Height Module diagram

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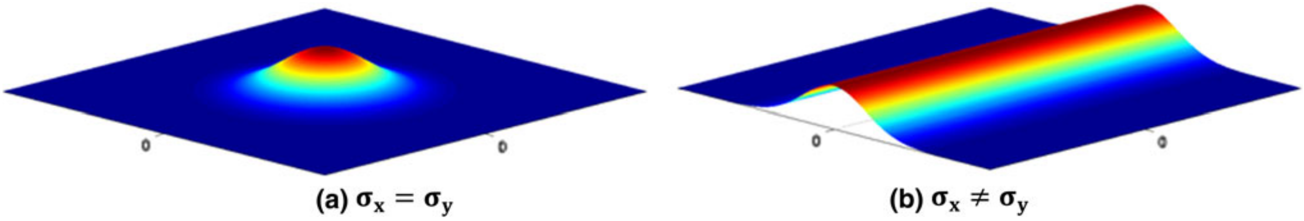
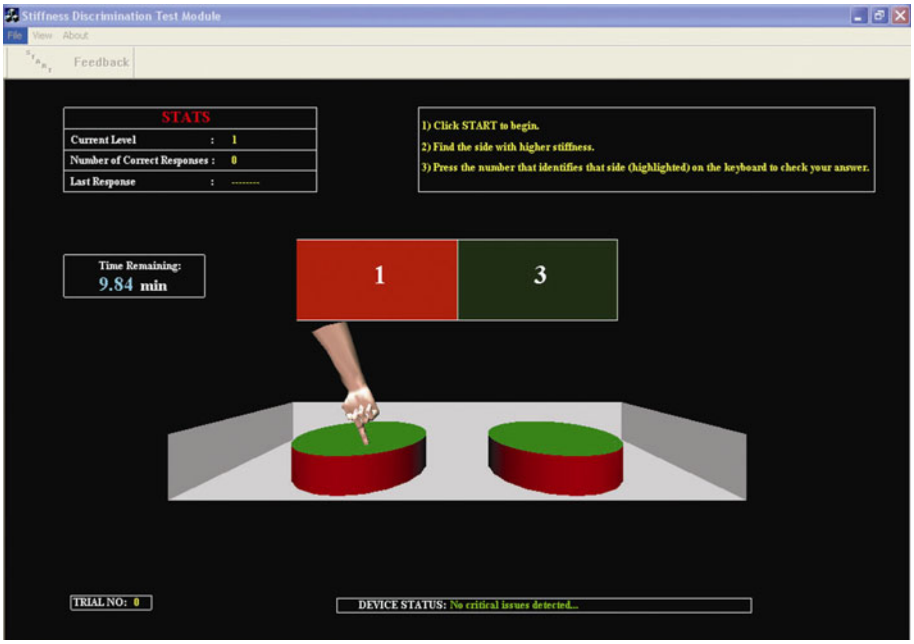


(a) $\sigma_x = \sigma_y$

(b) $\sigma_x \neq \sigma_y$

Fig. 5 Gaussian curves centered at (0, 0). **a** $\sigma_x = \sigma_y$. **b** $\sigma_x \neq \sigma_y$

Fig. 6 Stiffness discrimination haptic module screen shot



STATS
Current Level : 1
Number of Correct Responses : 0
Last Response : --------

1) Click START to begin.
2) Find the side with higher stiffness.
3) Press the number that identifies that side (highlighted) on the keyboard to check your answer.

Time Remaining: 9.84 min

TRIAL NO: 0

DEVICE STATUS: No critical issues detected...

Fig. 7 Stiffness discrimination diagram

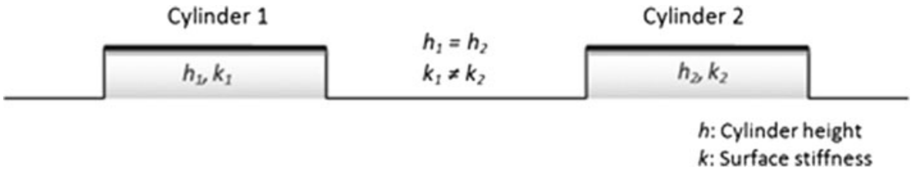


Fig. 8, users must find the direction of maximum tension by touch.

In the fascial drag module, the user touches the palpable surface and moves horizontally in different directions. The direction that they are moving toward at any instant is displayed on the indicator. The task is to find the direction that is hardest to push against.

As shown in Fig. 9, when the user touches the palpable surface, an anchor point (O) is fixed at that point of touch and as the user moves to another point (O'), without removing contact, the user's finger is pulled toward the anchor point with a force that is calculated by:

$$F = -kr \tag{2}$$

where r is the position vector from O to O', k is the stiffness constant of the spring in the direction of movement. This variable stiffness constant is a function of the orientation of r and is calculated as:

$$k = (1 - N)k_{\text{initial}} + Nk_{\text{final}} \tag{3}$$

where $N (0 \leq N \leq 1)$ is the weighting function that ensures a continuous transition between minimum and maximum value (k_{initial} and k_{final}) of the spring constant and is calculated as:

$$N = \begin{cases} \frac{1}{\pi}(2\pi - |\alpha_i - \theta|) & \text{if } |\alpha_i - \theta| > \pi \quad i = 1, 2, \ldots, 8 \\ \frac{1}{\pi}|\alpha_i - \theta| & \text{if } |\alpha_i - \theta| \leq \pi \quad i = 1, 2, \ldots, 8 \end{cases} \tag{4}$$

where α_i and θ are the angles that the pre-specified direction vector for that trial and r make with the horizontal, respectively. This pre-specified direction is chosen to be the direction that is hardest to push toward out of the

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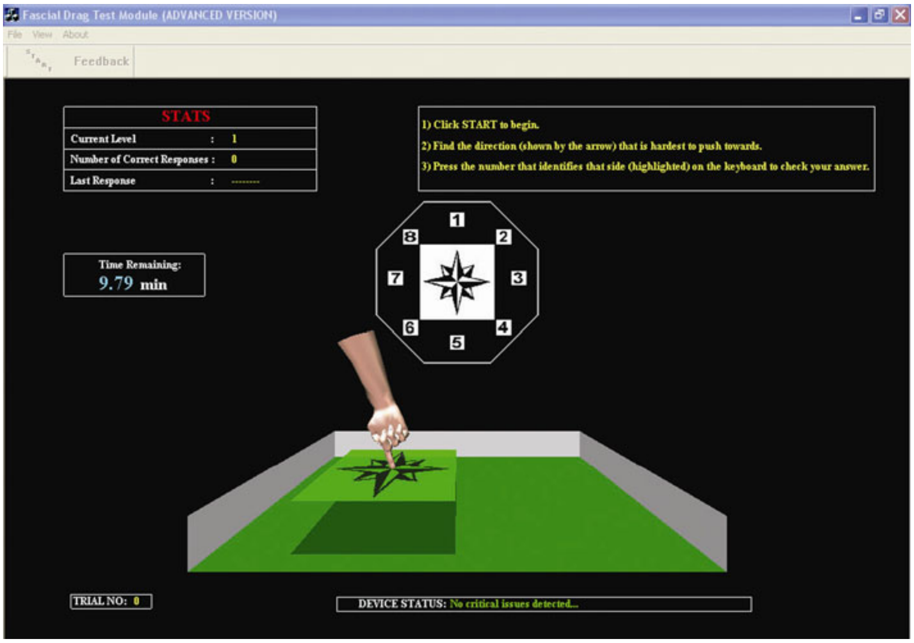

STATS

Current Level : 1

Number of Correct Responses : 0

Last Response : --------

1) Click START to begin.

2) Find the direction (shown by the arrow) that is hardest to push towards.

3) Press the number that identifies that side (highlighted) on the keyboard to check your answer.

Time Remaining: 9.79 min

TRIAL NO: 0

DEVICE STATUS: No critical issues detected...

Fig. 8 Fascial drag haptic module screen shot

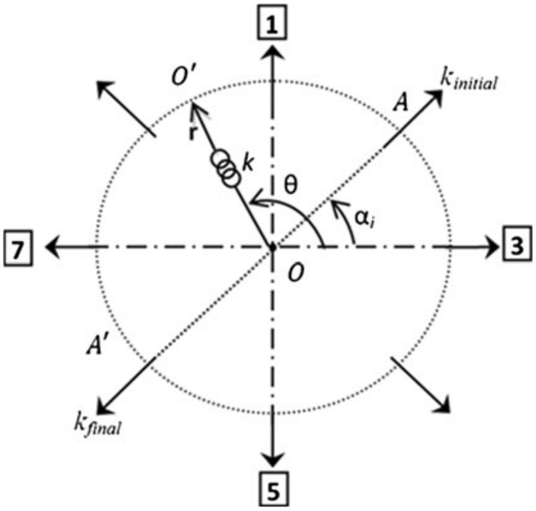

Fig. 9 Fascial drag haptic module diagram

possible eight directions. It should be noted that calculating the spring constant in this way creates an axis of symmetry, AA' in Fig. 9. As the level of difficulty increases, the difference between k_{initial} and k_{final} decreases, therefore making it more difficult to find the hardest direction to push toward.

As mentioned in the clinical relevance section, using fascial drag for diagnosis is an advanced form of palpation. Therefore, based on expert opinions, we designed a beginner version of this module that includes only four directions to choose from instead of eight. The model for the beginner version is the same as described above. The beginner version of this module was used in the evaluations reported later.

3.4 Ropey haptic module

Clinical relevance The term ropey is hard to understand, teach, and feel. This module helps the user get acquainted with the physical meaning of the term and practice identification of ropey tissue with finer and finer degrees of fibrous size and motion. Ropey tissue is associated with chronic overuse of a muscle/tissue by repetitive stress or injury. The tissue hypertrophy and fibrous texture is the body's reaction to stress, which may contribute to a patient's somatic dysfunction. Ropiness is a tissue property that is used and taught in clinical practice to differentiate tissue textures (Degenhardt et al. 2005).

Model The purpose of this module is to train the palpatory diagnosis skill of identifying ropey tissue. Ropey areas in tissue are associated with regions of somatic dysfunction. This module helps the user to identify ropey tissue with progressively finer degrees of motion. Ropey tissue is fibrous with one palpable rope that moves under the palpator's finger. As shown in Fig. 10, two identical ropes are presented in this module, but only one moves under the finger. When touched by the user, the corresponding half of the palpable surface is covered by a non-haptic 3D rectangle to prevent visual cues.

In the ropey module, the users identify the bump that moves when they touch and apply force. The bumps used are constructed the same way as described in the Bump Height Haptic Module, with Gaussian-smoothed edges. The movable bump in this module simulates the movement and feeling of a muscle bundle underneath the skin when touched and pressed whereas the stationary one represents a bony structure. The movable bump is simulated as a

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string-like material that is attached with a spring and has only one degree-of-freedom, translation in the horizontal (Fig. 11). F is the force applied by the user and k is the stiffness of the spring. As the difficulty level increases, the stiffness of the spring becomes higher, restricting the amount of movement. Therefore, with increasing levels, it becomes harder to differentiate the movable bump (ropey) from the stationary one (boney).

3.5 Pitting edema haptic module

Clinical relevance Identification of boggy and edematous tissue is an important skill in physical examination and in OMM. Bogginess is a palpable sponginess in tissue, resulting from congestion due to increased fluid content. Bogginess and edema are associated with acute inflammation, fluid stasis, and/or tissue injury. In physical examination, palpable edema is used in the detection of fluid-overload states, such as in renal failure. Palpation of bogginess and edema is used in the identification and diagnosis of somatic dysfunction (DiGiovanna and Schiowitz 1991), such as ankle sprain. A goal of OMM is to facilitate movement of stagnant fluid in order to promote healing to the tissue.

Model The purpose of this module is to train users in the identification of a spectrum of tissue textures from boggy to pitting edema. As shown in Fig. 12, the users train to identify one of two surfaces that deforms depending on the amount and the period of the applied force. Realistic soft tissue deformation is represented by viscoelastic engineering principles (Fung 1993). Different levels of pitting edema are simulated by adjusting the relaxation time of the surface after the force is removed.

One of the surfaces starts as a representation of boggy tissue whereas other surface represents a high level of edema. Tissue with bogginess rebounds more quickly than tissue with pitting edema and is modeled via spring constants with no damping. Bogginess is acute with inflammatory tissue and fluid buildup and is often associated with tissue fibrosis. Bogginess, along with ropiness, is also a tissue property that is used and taught in clinical practice to differentiate tissue textures (Degenhardt et al. 2005).

The deformation and force feedback to the user are calculated by using a Kelvin body (Fig. 13) which closely simulates stress relaxation and creep properties of a real human viscoelastic soft tissue (Fung 1993):

$$F + \tau_{\varepsilon}\dot{F} = E_{\mathrm{R}}(u + \tau_{\sigma}\dot{u}) \tag{5}$$

In (5), τ_{ε} is the relaxation time for constant strain, τ_{σ} is the relaxation time for constant stress, and E_{R} is the relaxed elastic modulus. They are calculated as:

$$\tau_{\varepsilon} = \frac{\eta_1}{\mu_1} \quad \tau_{\sigma} = \frac{\eta_1}{\mu_0}\left(1 + \frac{\mu_0}{\mu_1}\right) \quad E_{\mathrm{R}} = \mu_0 \tag{6}$$

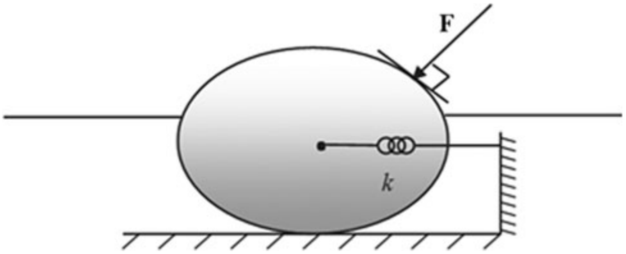
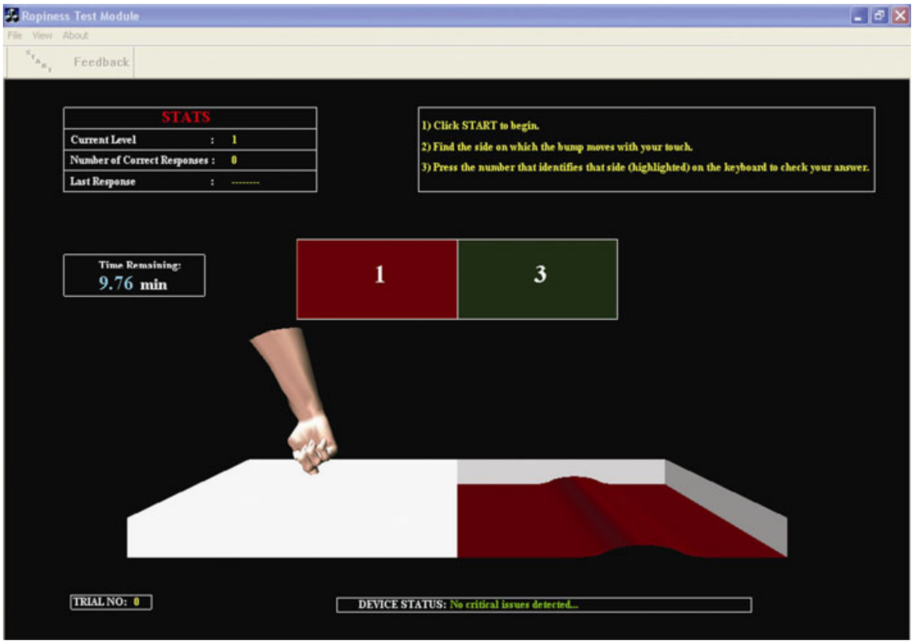


Fig. 11 Ropey haptic module Diagram



STATS

Current Level : 1

Number of Correct Responses : 0

Last Response : --------

1) Click START to begin.

2) Find the side on which the bump moves with your touch.

3) Press the number that identifies that side (highlighted) on the keyboard to check your answer.

Time Remaining: 9.76 min

TRIAL NO: 0

DEVICE STATUS: No critical issues detected...

Fig. 10 Ropey haptic module screen shot

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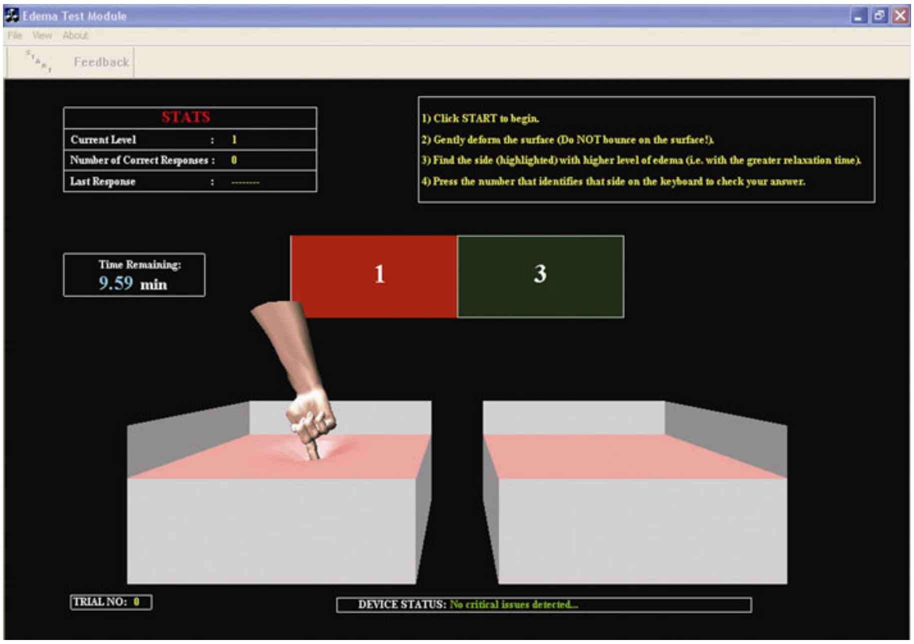

STATS

Current Level	:	1
Number of Correct Responses	:	0
Last Response	:	--------

1) Click START to begin.
2) Gently deform the surface (Do NOT bounce on the surface!).
3) Find the side (highlighted) with higher level of edema (i.e. with the greater relaxation time).
4) Press the number that identifies that side on the keyboard to check your answer.

Time Remaining: 9.59 min

TRIAL NO: 0

DEVICE STATUS: No critical issues detected...

Fig. 12 Pitting edema haptic module screen shot

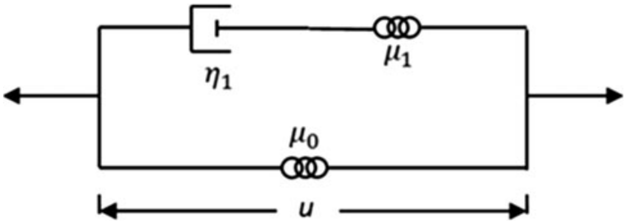

Fig. 13 Kelvin body diagram (Fung 1993)

where η_1 is the damping coefficient of the damper, and μ_0 and μ_1 are the spring constants in Fig. 13. The initial condition for (5) is as follows:

$$\tau_\varepsilon F(0) = E_R \tau_\sigma u(0) \tag{7}$$

The only difference between the two surfaces in Fig. 12 is that they are represented as Kelvin bodies with different damping coefficients, therefore different relaxation times. As the level of difficulty increases, however, the difference between the damping coefficients decreases, making it difficult to differentiate which side has the higher level of edema.

This module has a unique characteristic in that the users receive haptic and visual feedback at the same time since the method of identifying a pitting edema is performed both by touch and visually. The rest of the modules require users to solely rely on their haptic sense and visual feedback is only given in the case of an incorrect answer.

3.6 Bump location haptic module

Clinical relevance This module helps users explore a surface and find a region of increased stiffness. The ability to detect an area of different tissue quality and the identification of somatic dysfunction are fundamental to the practice of OMM (DiGiovanna and Schiowitz 1991). This concept can be difficult for any student who is untrained in palpation.

Model The purpose of this module is to train the palpatory diagnosis skill of locating patient tissue with differing stiffness than surrounding tissue without graphical cues. Stiffer regions or areas with increased tissue tension may imply an area of somatic dysfunction. As shown in Fig. 14, users find the location of a stiffness bump (as opposed to a contour bump).

In this module, the bump is defined by modifying (1), in such a way that the amplitude of the Gaussian function corresponds to the maximum stiffness value of the bump (instead of the maximum height of the contour in the Bump Height Haptic Module). Figure 15 shows the visualization of a stiffness bump, derived from Fig. 5a. A constant stiffness value is added to this function in order to have a background with a non-zero stiffness value. This enables the comparison of the bump stiffness to the background while the user palpates the surface area to locate the region with the bump. There are eight different regions in which the single stiffness bump could be located. The computer randomly picks the location of the bump after each trial. The user is asked to identify the region where the bump is located by feel only. As the difficulty level increases, the maximum stiffness of the bump becomes closer to the background stiffness value, therefore making it more difficult to locate the stiffness bump.

In order to evaluate the system, an evaluation study was performed, and both quantitative and qualitative data were

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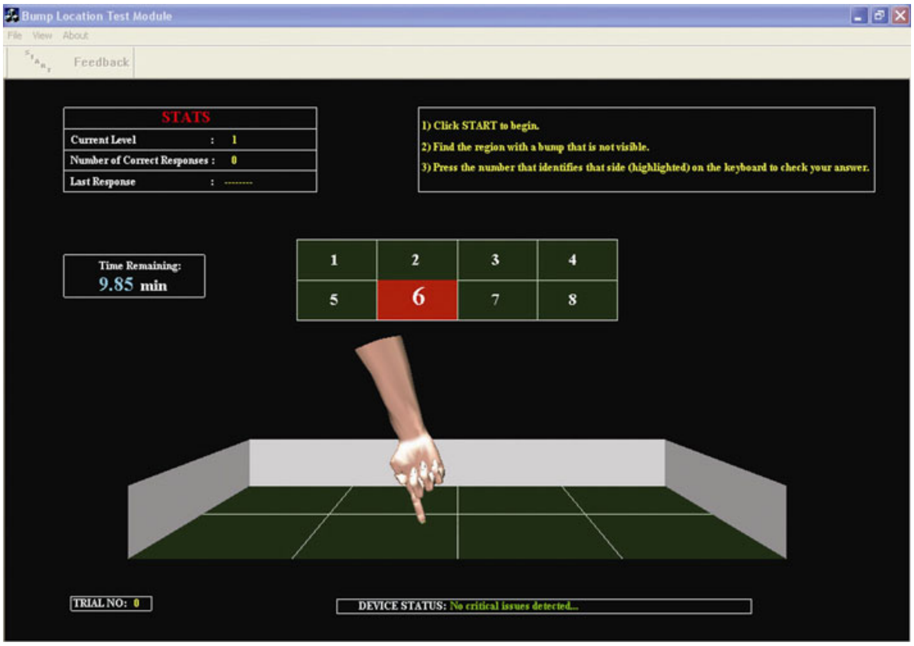

STATS

Current Level : 1

Number of Correct Responses : 0

Last Response : --------

1) Click START to begin.

2) Find the region with a bump that is not visible.

3) Press the number that identifies that side (highlighted) on the keyboard to check your answer.

Time Remaining: 9.85 min

TRIAL NO: 0

DEVICE STATUS: No critical issues detected...

Fig. 14 Bump Location Haptic Module screen shot

collected for further processing. The following section details this evaluation study performed using all six modules described here.

4 Evaluation of the haptic modules

4.1 Experimental setup

The haptic modules evaluation experiments were run on a 1.8 GHz dual Pentium PC with 1 GB RAM and an NVIDIA GeForce Go 6600 video adapter. A PHANToM Omni® haptic interface displayed the haptic feedback to the subjects. The software was written using Microsoft Visual C++ and the OpenGL® graphic library. The haptic effects were implemented by using the SensAble OpenHaptics Toolkit.

4.2 Subjects

Twenty-two adult subjects (16 first-year and 6 second-year osteopathic medical students) from the Ohio University College of Medicine (OUCOM) participated the evaluations. Ohio University IRB approval was obtained for this experiment and all participating subjects signed an informed consent form. Subjects received $15 for their participation time.

4.3 Procedure

The experiment consisted of a single session using the six modules explained above. The modules were presented in random order for each participant. Participants were introduced to the modules before they started their session. The introduction for each module ended when the participant got one correct response on their own for each module. The time during the introduction was not recorded. They had 10 min to complete each module and were allowed to take breaks if desired by pausing the system. The participants were also allowed to choose the finger to palpate since the modules were designed to accommodate any finger of either hand. All participants were observed to use their dominant hand and finger during the trials.

Each participant completed a computer-based questionnaire upon completion of each module. The questionnaire (Table 1) included six questions which asked for user feedback on their experience with the modules. The participants were instructed to carefully read the goal and the clinical relevance of each module that were presented as a pop-up message box before they started a particular module test. This was important in order for them to be able to rate the accomplishment of purpose (Q6 in Table 1) for the modules.

4.4 Results

The responses of the participants (first- and second-year osteopathic medical students) to the questionnaires are shown in Fig. 16. The results show that at least 59.1 % (lowest response for the Pitting Edema Haptic Module) of the participants thought that the current practice with any module would certainly help improve their palpatory skills. This percentage was highest for the Bump Height Haptic Module (86.4 %). None of the second-year students

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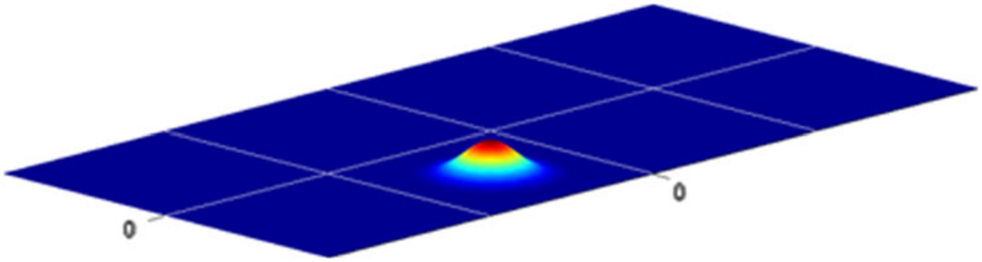

Fig. 15 A stiffness bump in the bump location haptic module (not visible to user)

Table 1 Evaluation Questionnaire

(Q1) Do you think this practice with the "… HAPTIC MODULE" will be of help to you in the development of your palpatory skills?		
Yes	Maybe	No
(Q2) Do you think *further practice* with the "… HAPTIC MODULE" will be of help to you in the development of your palpatory skills?		
Yes	Maybe	No
(Q3) Did you understand the instructions?		
Yes	Somewhat	No
(Q4) Is the user interface easy to understand? (For example, is the screen layout clear and easy to interpret?)		
Yes	Somewhat	No
(Q5) Would you like to use this module again?		
Yes	Maybe	No
(Q6) The purpose of this module is to train the palpatory diagnosis skill of …. How well do you think this module achieves that purpose?		
Likert-type scale (1-poorly, 10-very well)		

responded "No" to the question regarding the helpfulness of the current practice on any of the modules.

When students were asked whether they thought that future practice with the haptic modules would certainly help them improve their palpatory skills, at least 45.5 % (lowest response for the Pitting Edema haptic module) responded "Yes." This percentage was highest for the Bump Location Haptic Module (95.5 %). None of the second-year students responded "No" to the question regarding the helpfulness of future practice on any of the modules.

The majority (at least 77.3 %) of the students thought that the instructions on the module screens were clear. When the students were asked about the user interface, the majority (at least 86.4 %) responded that it was clear and easy to interpret.

Results also showed that when the students were asked whether they would like to use the modules in the future for training at least 90.9 % of them answered "Yes" or "Maybe" (lowest response for the Pitting Edema haptic module). This percentage reached to 100.0 % for the Bump Location Haptic Module.

An independent samples *t* test revealed no significant difference between the first- and second-year medical students when the achievement of purpose rating was compared (all $p > 0.21$). The pooled data showed that the achievement of purpose rating for the Pitting Edema Haptic Module was the lowest (6.27/10). For the remaining modules, the lowest rating was for the Fascial Drag haptic module (7.91/10), and the highest rating was for the Bump Height Haptic Module (8.82/10).

The average mastery levels attained by the students, and average trial times are shown in Figs. 17 and 18, respectively. The means of the mastery levels reached by second-year students were higher as compared to the first-year students except in the Fascial Drag Haptic Module. However, an independent samples *t* test showed that this difference was not statistically significant (all $p > 0.08$). Comparing the average trial times, the first-year students had higher average trial times than the second-year students. This difference was also not significant (all $p > 0.10$).

5 Discussion

Experienced palpators can acquire information on tissue tone, motion, and assessment of symmetry by means of a single, almost simultaneous, palpatory procedure. On the other hand, in the case of students and trainees, each

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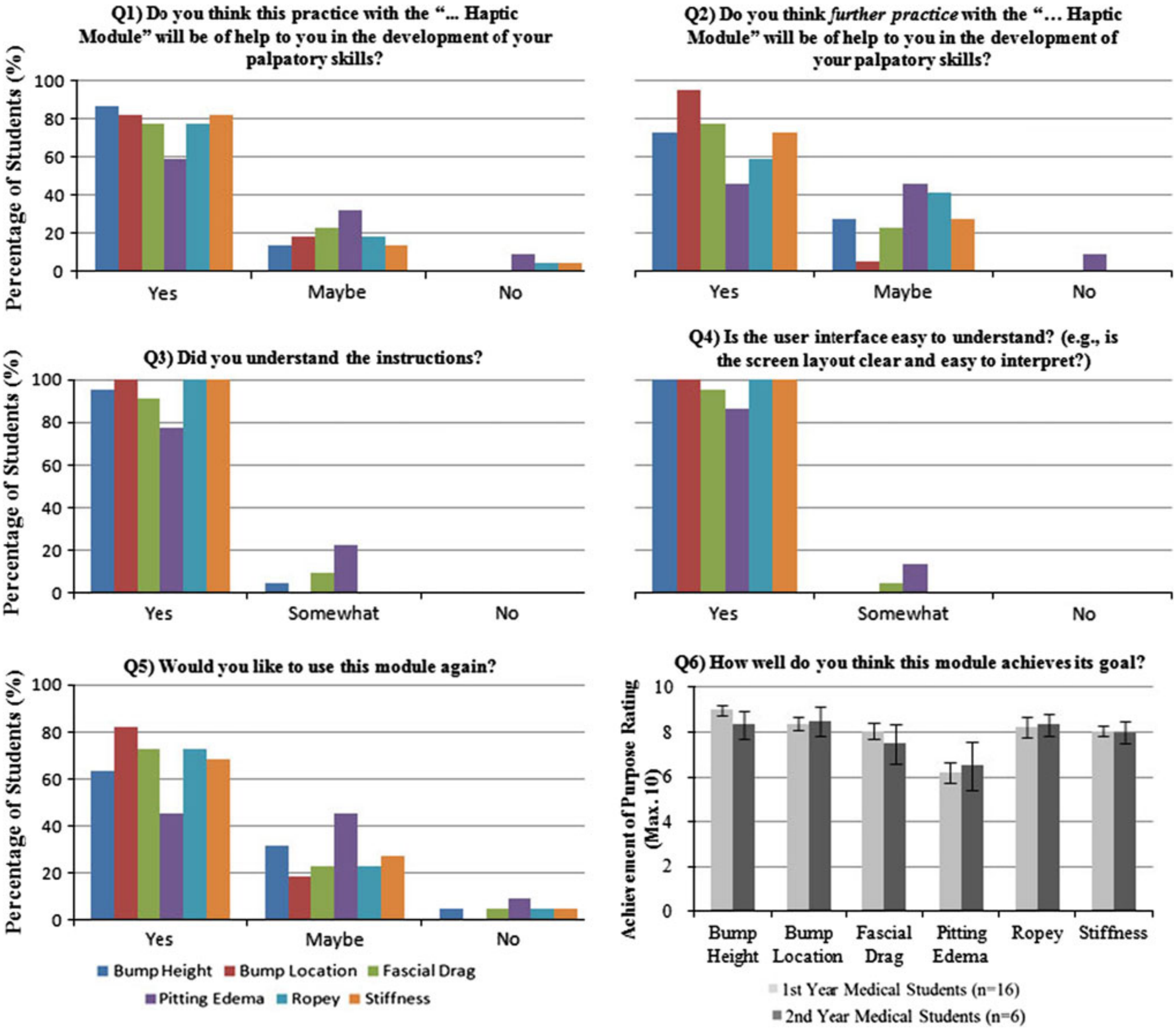

Fig. 16 Haptic modules evaluation results (standard error bars are shown for Q6)

element of palpation is studied as if they are independent procedures. Eventually, they combine these elements into one single procedure (Denslow 1964). Therefore, developing tools, such as the haptic modules described in this article, for students of medical and related professions that targets training different aspects of accurate palpation is an important step in improving palpation skills. Then, the individuals can blend these trained elements together in order to become proficient palpators. These tools must be objective to eliminate any confusion during the learning process. There are many (out of classroom) objective methods that are still recommended for students to improve their tactile and kinesthetic skills such as feeling a hair under a piece of paper, picking head, and tails of a coin by touch, recognizing the change in weight using birdshot, etc. (Allen and Stinson 1941). The modules were designed in such a way that they compose objective exercises that make up some of the elements of palpation as detailed in this article.

These modules enable students to spend as much time as they need to improve their palpatory skills without any pressure due to time or instructors who may expect them to perform well in front of their peers. Sufficient time and unlimited opportunity to make mistakes during practice sessions can help students in two different ways: (1) They learn how to focus their minds on the sensation resulting from every single touch, and (2) They could build confidence in their ability to palpate accurately. Concentration is very important, especially when it comes to detecting very subtle differences and/or changes. Lack of palpatory

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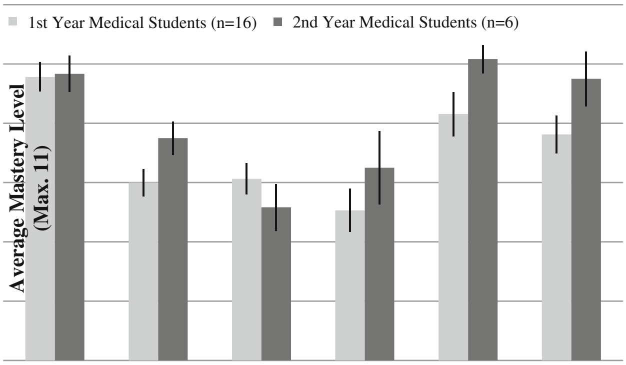

Fig. 17 Average mastery level (standard error bars are shown)

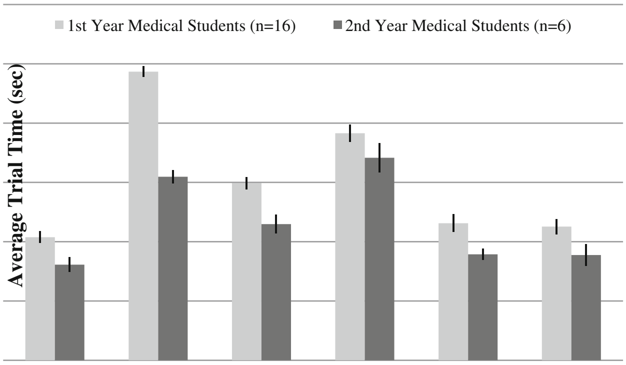

Fig. 18 Average trial time (standard error bars are shown)

confidence may be the main reason why students new to palpation rely on their visual estimation rather than the information they receive by palpation (Allen and Stinson 1941). The haptic modules add a repeatable component of science to the art of palpatory diagnosis.

The evaluation results were encouraging in the sense that the majority of the students are open to the idea that the modules may be of help to them in the future. The instructions on the screen and user interface had high rates of approval from all students. In simulations like the haptic modules where the users are required to perform simple basic tasks repetitively, as in many psychophysics experiments, it may be hard to attract potential users to train more extensively and keep them interested. As shown in the results section, at least 90.9 % of the students said that they would consider using the modules again. We believe that adding game-like elements with difficulty levels, time constraints to complete a task, and display of high scores for all users increases the competitiveness and desire to achieve more. Even the expert palpatory physicians, who tried the modules and gave informal feedback, found themselves competing with the computer and each other. Although we did not utilize it during the evaluations, the computer also keeps track of the best users and displays them to all users as the highest scorers. This is a feature that exists in almost all computer games and should drive students to do better on the modules.

The direction of the results from the objective data collected (Figs. 17, 18), even though not significant, is interesting in the sense that the second-year students tend to reach higher levels (except for the Fascial Drag haptic module) in less time as compared to first-year students. The reason behind this trend could be the amount of training the students receive during curricular training in osteopathic manipulation laboratories and palpation experience. To our knowledge, it was shown only for stiffness perception that it is a clinical skill which is developed with training and/or experience (Forrest et al. 2009). Even though this finding was confirmed for veterinary medicine, one may argue that the same outcome would hold for osteopathic and allopathic medicine as well since stiffness discrimination is an important component of palpation in all of these professions, for example, detection of problems such as muscles in spasm, lumps in breasts, testes, and abdomens. This tendency needs to be explored further for other modalities such as bump height or fascial drag detection. The difference in skill levels would possibly be more prominent between, for instance, the first- and fourth-year students or experts. Therefore, a study between students new to palpation (i.e., first-year medical students) and expert physicians in terms of the difference in mastery levels and average times to reach those mastery levels would be illuminating.

The evaluations also revealed that the least favorable module appears to be the Pitting Edema haptic module. As discussed previously, this module is the only one that provides haptic and visual feedback at the same time (in the remaining modules, users must depend solely on haptic feedback). This is in accordance with clinical diagnoses of edematous tissue. That is, the edema and its severity are defined by deforming the surface with pressure and then observing the time for the tissue to spring back. Expert physicians who tried the modules found this particular module quite helpful and expressed that they mostly used the haptic feedback to differentiate between two surfaces with different viscous properties. We, however, observed that the most of the students tried using the visual feedback rather than the haptic. This made it hard and frustrating to get the correct answer, especially when they reached higher levels when the visual comparison became hard. Some of the students confirmed this by stating that they relied mostly on visual feedback for the pitting edema module. As discussed previously, this could be related to the confidence levels of students. With continuing training and experience, they should be able to gain the confidence they need and learn to trust their palpatory skills. We do not think that visual dominance (Srinivasan et al. 1996) played an important role here since the students tried to visually

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compare relative, rather than absolute, speeds of recovery and amount of deformation of two surfaces. This outcome will be taken into account in future versions by removing the visual feedback from this module and, therefore, forcing users to rely on only their haptic perception.

In the current design, users can interact with the modules by one finger of the chosen hand. This keeps the cost of the system down. However, some procedures such as examination of vertebrae for existence of asymmetry and/or increased stiffness about an axis are generally performed using two fingers. In order to accommodate these training needs, a second haptic interface can easily be incorporated into the system to allow two-fingered palpation when it is necessary or desired.

6 Conclusion

We introduced six different haptic modules for palpatory diagnosis training: bump height, stiffness discrimination, fascial drag, ropey, pitting edema, and bump location. The main purpose of the modules described herein is to develop and improve the palpatory diagnosis skills of osteopathic medical students and practitioners. The modules, as a portable system consisting of a haptic device and a laptop PC, can be used as a stand-alone teaching station in a medical library where medical students can get access anytime to practice on their own. Overall, these modules are low cost and objective tools designed to train medical students and/or professionals to become better palpators.

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