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IMPLEMENTATION AND EVALUATION OF A VIRTUAL HAPTIC BACK

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ABSTRACT

A Virtual Haptic Back model has been developed by a cross-disciplinary team of researchers at Ohio University. Haptics gives the human the sense of touch and force from virtual computer models. The objective is to create a tool for medical and related education wherein students can train in the difficult art of palpation using virtual reality before approaching human subjects. Palpation is the art of medical diagnosis through the sense of touch. Haptic anatomy can be a key part in the future of medical school training; our goal is to add science to the art of palpation to improve osteopathic, physical therapy, and massage therapy training for students and practitioners.

Modeling of the Virtual Haptic Back took place in two steps. First, Cartesian back data was collected via the Metrecom Skeletal Analysis System digitizer. The back of a prone human subject was digitized, giving an array of three-dimensional points. Several methods were considered to smooth out the back data. Spline fitting with matched first and second derivatives was the chosen method. Once an acceptable graphical model was created, haptic feedback was added using the PHANToM haptic interface, allowing the human user to explore and feel the virtual back.

Experienced and novice palpators formally evaluated the Virtual Haptic Back to give us feedback for improvements. In addition, four Doctors of Osteopathy informally interacted with our model and gave verbal feedback. Our experts all suggested modeling underlying muscles and skeletal structure in addition to the skin layer for more realism. Once this is accomplished we will further program somatic dysfunction of various types in the Virtual Haptic Back for students to diagnose.

This article contributes to the state of the art in *Virtual Haptic Anatomy*. While other research groups are working in this area, our work is the first specifically aimed towards Osteopathic Medicine, Physical Therapy, and Massage Therapy students and practitioners.

KEYWORDS

haptics, haptic interface, haptics-augmented training, virtual haptic anatomy, virtual haptic back

1. INTRODUCTION

Haptics, the science of touch, is being applied in virtual reality environments to increase realism. An example of this is virtual reality computer games that use a force-reflecting joystick.

Haptics has been applied recently to education, most notably in medical education. 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. Further, haptic feedback was enabled via the PHANTOM haptic interface, allowing the user to interact with and feel the virtual model. No haptic implementation details are given in the paper. The Interventional Cardiology Training Simulator (Shaffer et al., 1999) links technical simulation with specific medical education content. A virtual reality-based simulator prototype for the diagnosis of prostate cancer has been developed using the PHANTOM haptic interface (Burdea et al., 1999). An earlier tumor palpation VR simulation was developed by Langrana (1997). The Immersion Corporation (www.immersion.com) has developed haptic interfaces for injection training and sinus surgery simulation. Delingette (1998) is working on realism in modeling human tissue for medical purposes. The GROPE Project (Brooks et al., 1990) has developed over 30 years a 6D haptic/VR simulation of molecular docking. The SPIDAR haptic interface has been adapted to serve as "the next generation education system" (Cai et al., 1997), although the authors do not elaborate on the type of education intended.

A group at the University of Ioannina in Greece is involved with virtual learning environments including a Power Glove with tactile feedback to "build a theoretical model for virtual learning environments, expanding constructivism and combining it with

experiential learning" (Mikropoulos and Nikolou, 1996). A research group at the Ohio Supercomputing Center has applied haptics in virtual environments to improve tractor safety by training young rural drivers (Stredney et al., 1998); their results show haptics increases training effectiveness. Haptics has been applied to make virtual environments accessible to blind persons (Jansson et al., 1999). Affordable haptic interfaces have been implemented to augment the teaching and learning of high school physics (Williams et al., 2001). Also, the effectiveness of virtual reality (without haptics) has been demonstrated in the learning process (North, 1996).

The Virtual Haptic Back (VHB) is an interdisciplinary project among three Ohio University colleges: Engineering, Osteopathic Medicine, and Health & Human Services. The purpose of the VHB is to develop a realistic haptic/graphical model of the human back that can be used for palpation in medical training. Palpation is the art of medical diagnosis through the sense of touch. Our goal is to add a component of science to the art of palpatory diagnosis. Current target applications are the diagnoses of both somatic dysfunction and movement dysfunction; we are interested in general haptic anatomy in future work.

This article presents the graphical and haptic aspects of implementing the VHB, followed by VHB evaluation by experienced and novice palpators. The major contribution of this work is as an initial step towards the big goal of *Virtual Haptic Anatomy* for Osteopathic Medicine, Physical Therapy, and Massage Therapy students and practitioners.

2. BACK MODELING

This section presents the graphical modeling of a subject human back via measurements by the Metrecom Skeletal Analysis System (SAS), followed by our method to smooth this data for use in the VHB graphics.

2.1 Metrecom Skeletal Analysis System

The purpose of VHB is to train medical students in the art of palpation. With this in mind, the VHB team set out to match the model to reality as closely as possible. The back of a volunteer subject was measured using a Metrecom Skeletal Analysis System (SAS) made by Faro Technologies Inc (see Fig. 1).



Figure 1. Metrecom SAS

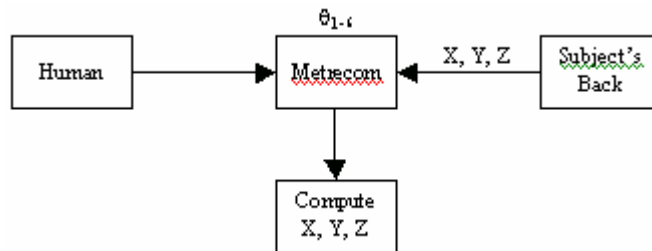


Figure 2: Metrecom SAS Flow Diagram

The Metrecom SAS is a mounted electrogoniometer digitizer that reads and stores 3D position data. The electrogoniometer is a user-powered, six degree-of-freedom arm. A potentiometer is located at each pivot point. As the user moves the arm, the resistance in each potentiometer varies, resulting in a certain voltage. The computer reads these voltages, determines the corresponding joint angles, and outputs a Cartesian point. The first Metrecom arm freedom is a 1-dof waist rotation about its base. The remaining arm consists

of a 1-dof shoulder joint, a 1-dof elbow joint, and a 3-dof wrist joint. The position sampling is time-dependent, acquiring 15 points per second.

The Metrecom SAS was developed as a measurement tool for both spinal curvature and flexibility, and joint range of motion. For our purposes, the Metrecom SAS serves solely as a 3D digitizer for a static human back. A flow diagram for the Metrecom SAS operation is pictured in Fig. 2. The human user moves the SAS pointer over the prone subject's back, in nine horizontal strips. A computer reads the six joint angles θ_1 - θ_6 and calculates the corresponding X, Y, Z locations.

2.2 Smoothing

The raw data consisted of an x , y , and z array for the surface back points recorded. The time dependency of the recording resulted in awkward spacing of the data points: they appeared to be randomly spaced as opposed to having a grid-like orientation. To remedy this, the software SigmaPlot (SPSS Science, Chicago, IL) was used to align the x , y , and z arrays in a grid. Each of the nine horizontal strips of data was divided into 100 Cartesian points, resulting in 900 total data points. The data was stored as a text file and copied to Visual C++ for use in the first version of VHB. It was then copied into a Matlab program for easier manipulation. A Matlab rendering of the original data is shown in Fig. 3.

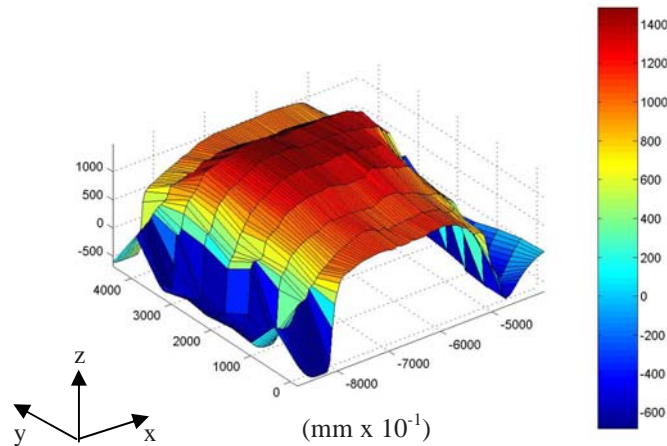


Figure 3. Matlab Rendering of Raw Data VHB

The first VHB left much, graphically and haptically, to be desired. This attempt was modeled using Ghost[®] SDK's TriPolyMesh command (SenseAble Technologies, 1997). This allows the programmer to create a triangular mesh from the 3D data. As seen in Fig. 4, the rendering was smooth along the x -axis (i.e. horizontally), but not smooth along the y -axis (vertically). A mathematical interpretation of the data was desired, for interpolation purposes, and as a more compact and less discrete way to describe the back. As previously stated, there were nine horizontal rows of data with 100 points each (see Fig. 5). The points are located across the width of the back, starting just below the neck (T2 vertebra) and ending in the lower lumbar region (L2 vertebra).

Since the data is smooth in the x direction (left-to-right on the back), emphasis lies on smoothing the y direction (up and down the back). We determined 100 individual curve fits in the y direction for smoothing purposes since each horizontal row of data contained 100 points each.

Originally, an eighth order polynomial was applied to fit the nine data points (100 times). The curve is smooth and satisfies all data points, but dips in the upper back region,

as can be seen in Fig. 6. The data points in Figs. 6-8 correspond to the y direction up and down the back; the left-most point is measured at the L2 vertebra and the right-most point is measured at the T2 vertebra.

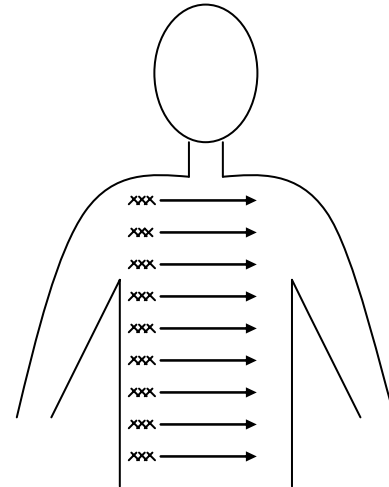
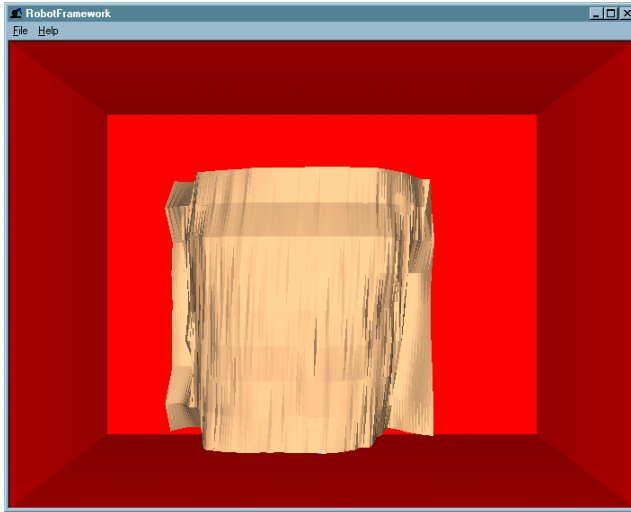


Figure 4. C++ View of Raw Data VHB

Figure 5: Original Data Locations

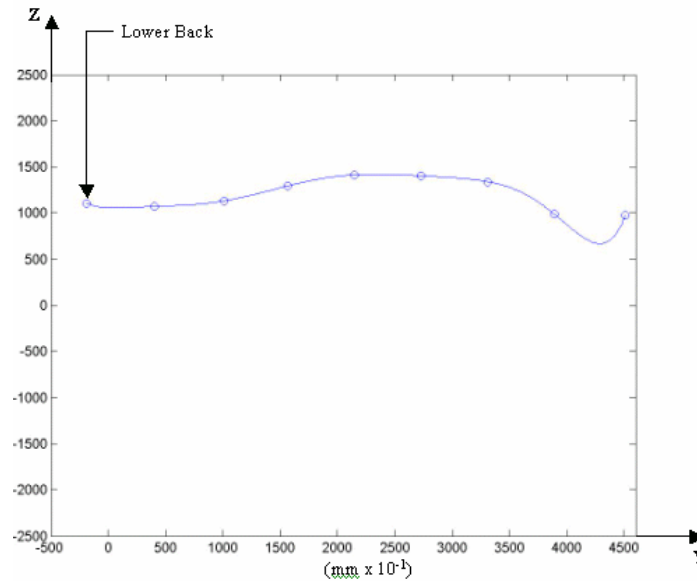


Figure 6. Eighth Order Curve Fit

To fix the dip problem of Fig. 6, three separate curve fits were generated to fit the back. The middle curve was a quartic polynomial to fit point three through point seven of

the original eighth order curve. The first and third curves used the first three and last three data points, respectively, to generate quadratic curves. The endpoints of the middle section are reused in order to connect each curve with its predecessor. The results of this method are shown in Fig. 7.

In Fig. 7 it is clear that the three separate curve fits result in a visible discontinuity (the lower back discontinuity is not as visible). Therefore, we chose to match the three polynomials at their junction points not only in position but also matching their first and second derivatives across the two junction points. With the additional derivative matching constraints, the first and third polynomials must be of third order, and the middle polynomial is increased to sixth order. This will not only smooth the back in the y direction and include all the original data points, but it will create a smooth transition between the three different curves (see Fig. 8). Equations (1-3) represent the three curves plotted in Fig. 8:

$$z_A(y) = a_1 + b_1y + c_1y^2 + d_1y^3 \quad (1)$$

$$z_B(y) = a_2 + b_2y + c_2y^2 + d_2y^3 + e_2y^4 + f_2y^5 + g_2y^6 \quad (2)$$

$$z_C(y) = a_3 + b_3y + c_3y^2 + d_3y^3 \quad (3)$$

where $z_A(y)$, $z_B(y)$, and $z_C(y)$ are the three polynomials, a_{1-3} , b_{1-3} , c_{1-3} , d_{1-3} , e_2 , f_2 , and g_2 are the unknowns, and y is the independent variable. Equations (1) and (3) are third order, and (2) is sixth order, chosen to match the number of polynomial constants with the number of given constraints. Four constants from (1), seven constants from (2), and four constants from (3) match the fifteen constraints, discussed next.

Each of the position data points must lie on the curve: three for the first curve, five for the second curve, and three for the third curve. To fix the discontinuity seen in Fig. 7,

we force both the first derivatives and second derivatives to match for different polynomials meeting at the two junctions. The constraints are listed below with y_{1-9} and z_{1-9} representing the data points and a_{1-3} , b_{1-3} , c_{1-3} , d_{1-3} , e_2 , f_2 , and g_2 are the constants to be determined for each of the three polynomials. Equations (4) through (14) are position constraints, (15) and (16) match the first derivatives, and (17) and (18) match the second derivatives.

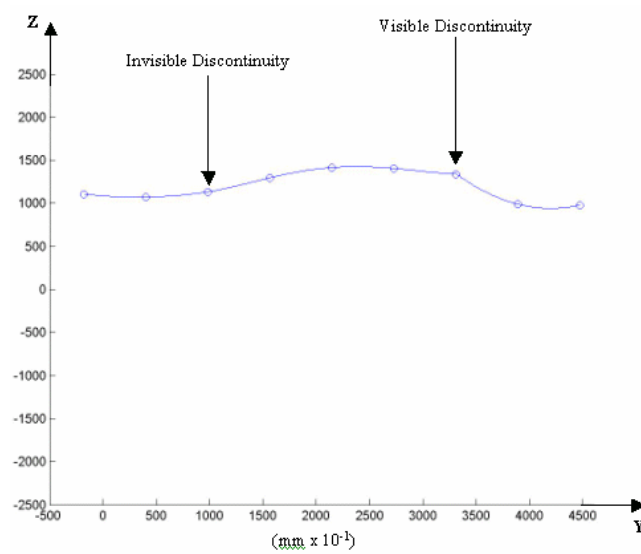


Figure 7: Three Separate Curve Fits

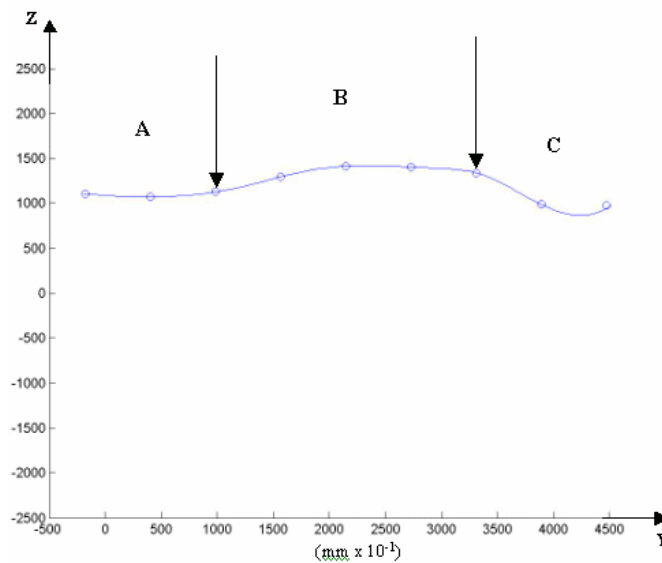


Figure 8: Matching First and Second Derivatives

$$z_1 = a_1 + b_1 y_1 + c_1 y_1^2 + d_1 y_1^3 \quad (4)$$

$$z_2 = a_1 + b_1 y_2 + c_1 y_2^2 + d_1 y_2^3 \quad (5)$$

$$z_3 = a_1 + b_1 y_3 + c_1 y_3^2 + d_1 y_3^3 \quad (6)$$

$$z_3 = a_2 + b_2 y_3 + c_2 y_3^2 + d_2 y_3^3 + e_2 y_3^4 + f_2 y_3^5 + g_2 y_3^6 \quad (7)$$

$$z_4 = a_2 + b_2 y_4 + c_2 y_4^2 + d_2 y_4^3 + e_2 y_4^4 + f_2 y_4^5 + g_2 y_4^6 \quad (8)$$

$$z_5 = a_2 + b_2 y_5 + c_2 y_5^2 + d_2 y_5^3 + e_2 y_5^4 + f_2 y_5^5 + g_2 y_5^6 \quad (9)$$

$$z_6 = a_2 + b_2 y_6 + c_2 y_6^2 + d_2 y_6^3 + e_2 y_6^4 + f_2 y_6^5 + g_2 y_6^6 \quad (10)$$

$$z_7 = a_2 + b_2 y_7 + c_2 y_7^2 + d_2 y_7^3 + e_2 y_7^4 + f_2 y_7^5 + g_2 y_7^6 \quad (11)$$

$$z_7 = a_3 + b_3 y_7 + c_3 y_7^2 + d_3 y_7^3 \quad (12)$$

$$z_8 = a_3 + b_3 y_8 + c_3 y_8^2 + d_3 y_8^3 \quad (13)$$

$$z_9 = a_3 + b_3 y_9 + c_3 y_9^2 + d_3 y_9^3 \quad (14)$$

$$b_1 + 2c_1 y_3 + 3d_1 y_3^2 = b_2 + 2c_2 y_3 + 3d_2 y_3^2 + 4e_2 y_3^3 + 5f_2 y_3^4 + 6g_2 y_3^5 \quad (15)$$

$$b_3 + 2c_3 y_7 + 3d_3 y_7^2 = b_2 + 2c_2 y_7 + 3d_2 y_7^2 + 4e_2 y_7^3 + 5f_2 y_7^4 + 6g_2 y_7^5 \quad (16)$$

$$2c_1 + 6d_1 y_3 = 2c_2 + 6d_2 y_3 + 12e_2 y_3^2 + 20f_2 y_3^3 + 30g_2 y_3^4 \quad (17)$$

$$2c_3 + 6d_3 y_7 = 2c_2 + 6d_2 y_7 + 12e_2 y_7^2 + 20f_2 y_7^3 + 30g_2 y_7^4 \quad (18)$$

Equations (4-18) were written in matrix/vector form (19) and the unknown polynomial coefficients (a_{1-3} , b_{1-3} , c_{1-3} , d_{1-3} , e_2 , f_2 , and g_2) were solved from this set of 15 linear equations in 15 unknowns.

$$\begin{bmatrix} 1 & y_1 & y_1^2 & y_1^3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & y_2 & y_2^2 & y_2^3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & y_3 & y_3^2 & y_3^3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & y_3 & y_3^2 & y_3^3 & y_3^4 & y_3^5 & y_3^6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & y_4 & y_4^2 & y_4^3 & y_4^4 & y_4^5 & y_4^6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & y_5 & y_5^2 & y_5^3 & y_5^4 & y_5^5 & y_5^6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & y_6 & y_6^2 & y_6^3 & y_6^4 & y_6^5 & y_6^6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & y_7 & y_7^2 & y_7^3 & y_7^4 & y_7^5 & y_7^6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & y_7 & y_7^2 & y_7^3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & y_8 & y_8^2 & y_8^3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & y_9 & y_9^2 & y_9^3 & 0 \\ 0 & -1 & -2y_3 & -3y_3^2 & 0 & 1 & 2y_3 & 3y_3^2 & 4y_3^3 & 5y_3^4 & 6y_3^5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 2y_7 & 3y_7^2 & 4y_7^3 & 5y_7^4 & 6y_7^5 & 0 & -1 & -2y_7 & -3y_7^2 & 0 \\ 0 & 0 & -2 & -6y_3 & 0 & 0 & 2 & 6y_3 & 12y_3^2 & 20y_3^3 & 30y_3^4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2 & 6y_7 & 12y_7^2 & 20y_7^3 & 30y_7^4 & 0 & 0 & -2 & -6y_7 & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ b_1 \\ c_1 \\ d_1 \\ a_2 \\ b_2 \\ c_2 \\ d_2 \\ a_3 \\ b_3 \\ c_3 \\ d_3 \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \\ z_7 \\ z_7 \\ z_8 \\ z_9 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (19)$$

Equation (19) was solved for each of the 100 strips of data to obtain the individual curves for the 100 vertical sections of the back. The final Matlab rendering is Fig. 9.

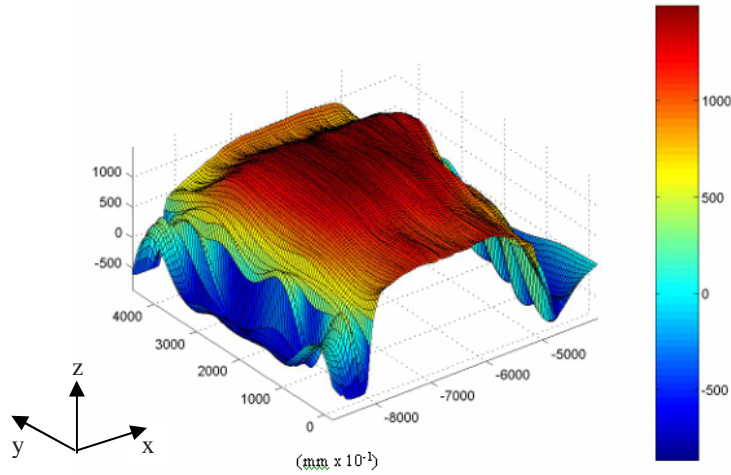


Figure 9. Matlab Rendering of Final Data

The rendering in Visual C++ is shown in Fig. 10. The discontinuous data due to unsteady measurement along the sides of the back have been eliminated between Figs. 9 and 10.

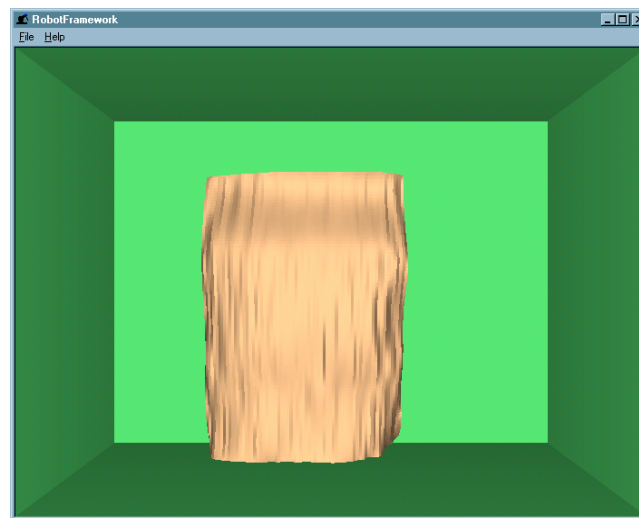


Figure 10. C++ Rendering of Final Data VHB

At this point a discussion on errors in our back model is warranted. First, in the lab it is impossible to measure the human back so quickly such that the subject can survive on

one breath of air. That is, the natural breathing of the human subject caused some error in our raw data measurements. We don't know how to quantify this error, but one can imagine the worst error case simply by breathing and registering the maximum displacement of the human back and chest. This error will be different for different subjects. Further, additional errors can be introduced by our data smoothing techniques presented above, accomplished to improve the graphics and haptics qualities of our model. Since we force the original data points to be met, we believe this source of error is bounded by the more significant case of breathing error. In any case, the (unknown) errors introduced do not pose a problem in our project since our aim is not to model a specific human back with high accuracy but rather to model a reasonable, generic human back for training purposes.

3. VHB IMPLEMENTATION

This section presents implementation of the VHB in virtual reality using the PHANToM haptic interface and graphics and haptics programming.

3.1 PHANToM Haptic Interface

The PHANToM haptic interface (Fig. 11) by SenseAble Technologies, Inc. operates like the Metrecom SAS but does more than yield Cartesian points. It uses the calculated position information to determine what forces to relay back to the user via its three motors. A flow diagram for the PHANToM is pictured in Fig. 12. The human finger moves the PHANToM to desired X, Y, Z Cartesian locations (sensed internally via joint encoders $\theta_1, \theta_2, \theta_3$); this Cartesian input is sent to a virtual computer model. The haptic/graphical software determines what Cartesian force vector F_X, F_Y, F_Z the human should feel and the PHANToM generates this force at the human finger (accomplished internally via joint torques τ_1, τ_2, τ_3).



Figure 11. PHANToM Haptic Interface

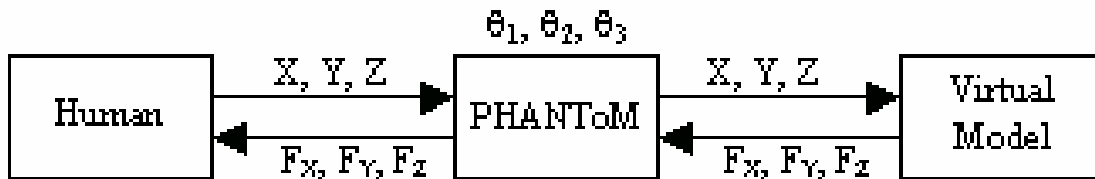


Figure 12. PHANToM Flow Diagram

3.2 Graphics and Haptics Programming

The first step in modeling the VHB using Ghost[®] SDK (the software used to program the PHANToM, SenseAble Technologies Inc., 1997), is to define what is included in the haptic scene. The Ghost[®] SDK uses OpenGL for 3D graphics. A pointer to the root of the desired scene graph is defined, and the haptic simulation is performed by a servo loop operating at a rate of 1kHz. The servo loop performs the following functions: 1) update the PHANToM node position in the scene graph, 2) update the dynamic state of all dynamic objects, 3) detect collisions between PHANToM nodes and geometric nodes in the scene graph, and 4) send resultant forces back to the PHANToM.

The VHB makes use of GHOST[®] SDK's `gstTriPolyMesh` command to define the back. The VHB position data is defined as three arrays (x , y , and z) in a header file. The inputs to `gstTriPolyMesh` are: 1) the number of total data points, 2) the position data, 3) the number of triangles in the mesh, and 4) the three points of each triangle in the mesh. The VHB workspace is contained using Ghost's `gstBoundaryCube` function, which confines the user's movement to a box shaped volume.

The haptic feedback is based on linear springs, normal to the surface of each triangle in the mesh. The spring constant is the same over the entire back, set for a reasonable feel. Part of our future work plans are to measure and implement a more realistic, nonlinear human tissue model (as in Delingette, 1998), including subcutaneous soft tissues and skeletal elements. These additional layers will be implemented in the VHB using force thresholds with the PHANToM.

4. VHB EVALUATION RESULTS

This section presents the results of our preliminary VHB evaluation study to measure project results and give us a basis for future improvements.

A significant improvement between the raw VHB and the smoothed VHB is both visible and palpable. The most significant improvement is in the vertical direction. In the C++ rendering of the raw data, the nine horizontal sample strips were visible and palpable (Fig. 4). The smoothing method of choice (curve fitting with matched derivatives vertically down the back) resulted in interpolated data. Since each strip of interpolated data was independent of the strip beside it, variance in the z -direction occurred at certain widthwise sections of the back. These vertical strips are visible in the final C++ rendering of the back (Fig. 10).

The evaluators were asked to rate both raw and smoothed versions of the VHB in the following categories: color, shading, graphic and haptic smoothness, graphic and haptic contour, stiffness, friction, and real-time interaction. They were asked to evaluate the VHB in each category on a scale of one (very unrealistic) to ten (very realistic). All of these performance measures were subjective, based on evaluator opinions; we have no method to objectively measure results in any of these categories.

Six experienced palpators and twenty novice palpators evaluated the VHB. All experienced palpators came from the Ohio University School of Physical Therapy. They were second year graduate students who had acquired standard palpations skills through practice and schooling. Any person inexperienced in the art of palpation was considered a novice. All novices for this experiment were students from the Ohio University College of Engineering. This study was not intended for statistical significance, rather as an initial

evaluation to give us areas for future improvement of our model. We wished to have more subjects, but six experienced palpators was all we could arrange in the project time frame.

Evaluation sheets were given along with a brief explanation of the VHB project. Brief PHANToM training was provided. Evaluators were given two evaluation sheets and instructed how to complete them, one for the raw VHB and one for the final VHB. General comments were strongly encouraged. Finally, the user was presented with both models, raw VHB first. Average results for both groups on both versions of the VHB are in Table I; Table II gives the associated standard deviations.

On average, experienced palpators rated raw VHB graphics 15.7% higher than novices. However, experienced palpators rated raw VHB haptics 8.4% lower than novices, due to their palpation expertise. High standard deviations resulted, varying from 1.25 to 3.02 on a scale of 10. This could be due to lack of experience using the PHANToM. None of the six experienced palpators had used the PHANToM before. Although they were briefly instructed, a few subjects commented that the device was hard to adapt to. This is not uncommon: past non-VHB demonstrations have resulted in similar comments.

	Novice Raw	Novice Final	Experienced Raw	Experienced Final
Graphics				
Color	5.90	7.10	6.50	7.33
Smoothness	4.40	6.75	5.50	6.50
Shading	5.70	7.35	6.58	6.60
Contour	5.25	6.95	6.00	6.67
Haptics				
Smoothness	5.05	7.00	6.17	6.50
Stiffness	6.40	7.25	5.00	6.17
Friction	5.95	7.45	5.33	5.50
Contour	6.25	7.70	5.17	5.33
Real-time Interaction	8.00	8.20	9.00	8.83

Table I. Raw and Final VHB Averages

	Novice Raw	Novice Final	Experienced Raw	Experienced Final
Graphics				
Color	1.74	1.37	2.26	2.25
Smoothness	2.26	1.52	2.59	3.08
Shading	1.81	1.39	2.25	2.51
Contour	2.07	1.90	2.61	2.58
Haptics				
Smoothness	2.28	1.75	1.47	2.07
Stiffness	1.39	1.25	2.53	2.64
Friction	2.24	1.28	3.01	3.02
Contour	2.31	1.75	2.79	3.08
Real-time Interaction	2.15	1.44	0.63	0.75

Table II. Raw and Final VHB Standard Deviations

In all categories (graphic and haptic), both groups rated the smoothed VHB as improved (with the exception of real-time interaction for the experienced palpators). Relatively speaking, the novice group rated the second version of VHB much more improved than did the experienced palpators. The percent differences in the averages for each category rated by both groups are shown in Table III.

	Novice (%)	Experienced (%)
Graphics		
Color	20.3	12.8
Smoothness	53.4	18.2
Shading	28.9	0.3
Contour	32.4	11.2
Haptics		
Smoothness	38.6	5.3
Stiffness	13.3	23.4
Friction	25.2	3.2
Contour	23.2	3.1
Real-time Interaction	2.5	-1.9

Table III. Percent Improvements from Raw to Final VHB

Both positive and negative feedback was given in the comments. Experienced palpators were more likely to make a comment, and were more detailed. As seen from the tables above, virtually all marks improved for the final, smoothed VHB. The fundamental theme in most comments was that the back must be modeled considering the underlying muscle and bone structure to help the VHB feel like an actual human back.

Now, the fact that the final, smoothed VHB is preferable to the raw version is not surprising. In fact, we would not consider using the raw VHB in the future just based on the modeling team's opinions and experience with the models. Again, the evaluation study was not intended to be statistically significant, but it was simply intended to improve our model in future work. The comments from evaluators, especially from our experienced subjects and doctors (see below) were the most valuable results from our evaluation study.

More sophisticated and long-term suggestions were offered by practicing osteopathic doctors with tactile specialties (four Doctors of Osteopathy (DOs) independently tested the raw and final VHB models, though they did not fill in a formal evaluation). The DOs also suggested programming haptic tissue and skeleton beneath the skin. Since the digitizing of a skeleton is not trivial, two of the DOs independently suggested programming different sized spheres to represent the spinous and transverse processes of the human spine. This eliminates the programming of parts of the skeleton that the palpator cannot ordinarily feel. This type of haptic modeling would enable the programming of different types of somatic dysfunction. Another suggestion to aid in palpation training is to turn off the graphical clues for different types of dysfunction, thus testing the student's ability to diagnose by feel.

5. CONCLUSION

This article has presented implementation and evaluation of the Virtual Haptic Back (VHB) by an interdisciplinary team of researchers and educators at Ohio University. We are involved in *Virtual Haptic Anatomy*, specifically for the purpose of providing a tool for students in medical and related fields to better train themselves in the art of palpatory diagnosis. Since the human sense of touch is generally less-developed than vision and hearing, we wish to add a component of science to the art of palpatory diagnosis, both in learning and practice.

The first-cut VHB has been implemented in virtual reality using a PHANToM haptic interface. The back model was measured, the position data was smoothed, and haptic feedback was added. We have concluded initial VHB evaluation by experienced and novice palpators.

Based on the VHB project evaluation, we will next add muscle and skeletal structure layers for the trainee to feel under the existing skin layer. This will require the development of a more advanced haptics model. We will then program various types of somatic dysfunction for students in various palpatory disciplines to practice their diagnoses. This next phase will conclude with evaluation to ensure project results meet the needs of students, professors, doctors, and other practitioners.

Some other research groups are involved in *Virtual Haptic Anatomy*. The major contribution of this article is our focus on Osteopathic Medicine, Physical Therapy, and Massage Therapy students and practitioners. No previous research group has taken this focus to date, according to our literature search.

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