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THE VIRTUAL HAPTIC HUMAN UPPER BODY

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ABSTRACT

The objective of this research is to create a movable, palpable virtual model of the dynamic human upper body, including the spine, shoulders, and arms skeletal structure, with dynamic pivot point and deformable skin. This Virtual Haptic Human Upper Body (VHHUB) model has realistic human motion with anatomically-accurate joint motion limits and a 71 degrees-of-freedom branching serial chain model. The aim is to provide realistic motions when an osteopathic medical student moves the virtual patient for palpatory diagnosis training. Medical trainees can thus practice feeling changes in human tissue due to motions, a common diagnostic technique.

1. INTRODUCTION

The VHB (Virtual Haptic Back) is one of the current research projects of the Interdisciplinary Institute for Neuromusculoskeletal Research at Ohio University, supported by the Osteopathic Heritage Foundation (Williams et al. 2003). The VHB is the first product to apply haptics (force and touch feedback to the user) and virtual reality (VR) technology to support research and medical student training in the field of osteopathic medicine, specifically palpatory diagnosis tasks. Haptics devices give a human user the sense of touch and force feedback from virtual computer models. The VHB system is shown in use in Figure 1, where the medical student is scanning the virtual patient mid-thoracic vertebrae for somatic dysfunctions.

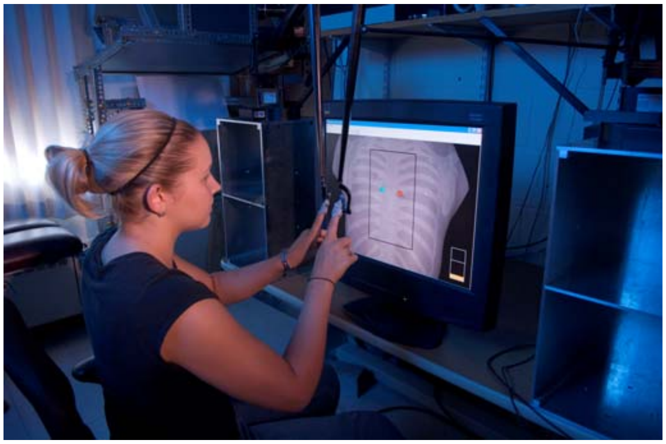


Figure 1. Medical Student with Virtual Haptic Back

The current VHB research objective is to create an innovative tool for medical education wherein students can train in the difficult art of palpatory diagnosis using virtual reality as a supplement to practice with human subjects. Palpatory diagnosis can change the condition of the human subject's back, interfering with diagnoses by multiple students. Therefore, VHB is adding repeatable science to osteopathic training via haptics technology and virtual reality. We are evaluating our product with human subjects in the lab and continuously refining the realism of VHB models based on feedback from osteopathic physicians and students. However, the current VHB model is a static model. Users can only feel the surface stiffness and 3D contour of the virtual back. In clinical situations, osteopathic physicians often use gross motion of the human upper body to create spine movement in order to find abnormal vertebrae. The purpose of this research is to create a user-movable virtual human upper body and incorporate haptics technology for training osteopathic medicine students to use gross motion techniques.

2. RELATED VIRTUAL HUMAN RESEARCH

Most virtual human research focuses on workspace and obstacle avoidance analysis. Human limbs are considered as the end-effectors. The majority of virtual human research studies the results of the end-effector movements. A research group in University of Iowa simulated a virtual human upper body by using an optimization-based control method. They minimized cost functions to obtain arm trajectories and used control points to achieve smooth limb movements and avoid obstacles (Abdel-Malek et al. 2004). Their algorithm is different from the traditional inverse kinematics method. Another group simulated dynamic athletic movements. They simulated athletes running, bicycling, and vaulting by using control algorithms. They used control algorithms to obtain desired joint angles of human limbs during athletic movements (Hodgins et al. 1995). Their research objective was to simulate virtual human athletes performing natural-looking movements. Their main focus was human limb movements. A Swiss research group analyzed human shoulders by using workspace constraints to simulate virtual human shoulder movements. They implemented the traditional inverse kinematics method to find the joint angles during shoulder motions and combined with workspace constraints to achieve natural human shoulder movements (Maurel and Thalmann 2000). These virtual human research goals were simulation of natural human limb movements and workspaces. The current Virtual Haptic Human Upper Body (VHHUB) incorporates individual vertebra movement coordinated to obtain overall motions of the shoulder, elbow, and other user-defined points. The intermediate joint angles of the VHHUB model are calculated in real time. Our early work in this area was documented in Chen et al. (2006).

3. THE VIRTUAL HAPTIC HUMAN UPPER BODY

The human skeleton can be considered a series of connected rotational links. This research focuses on the thoracic vertebrae (T1 to T12) as shown in Figure 2, lumbar vertebrae (L1 to L5), shoulders and two arms. Figure 3 shows our model for the human shoulder region.

To describe the translational and rotational relationships between adjacent links of the open kinematic chains, Denavit-Hartenberg (DH) notation (Craig 2005) will be used because of its strength in handling large numbers of degrees of freedom and because of its ability to systematically enable kinematic and dynamic analyses. The joint limit of each bone will be acquired from biomechanical human data (Kapandji 1974a; Kapandji 1974b; White and Panjabi 1990).

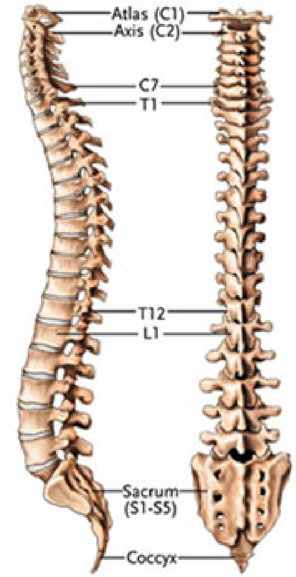


Figure 2. Anatomy of the Human Spine (from www.back.com/anatomy.html)

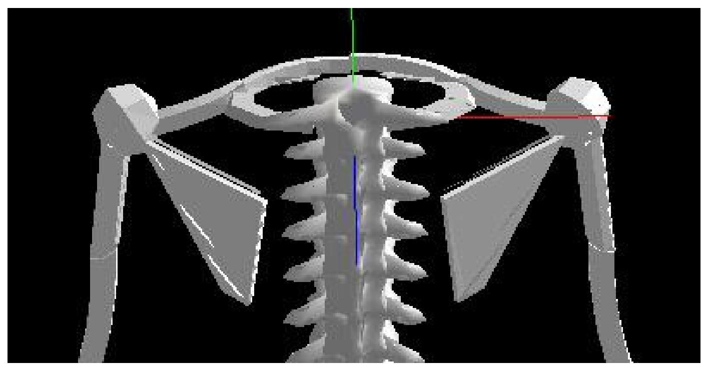


Figure 3. 3D Human Shoulder Model

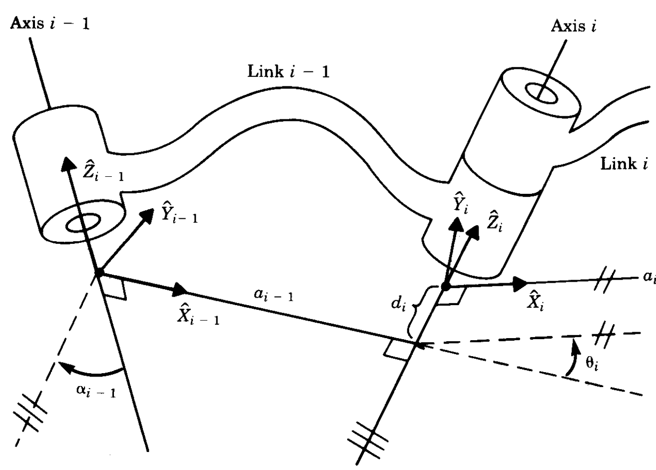


Figure 4. Joint Reference Frames for D-H Representation (from Craig 2005)

Consider Figure 4 where two consecutive joints are shown. The four parameters depicted in Figure 4 are:

a_{i-1}	distance from	Z_{i-1} to Z_i	measured along	X_{i-1}
α_{i-1}	angle between	Z_{i-1} and Z_i	measured about	X_{i-1}
d_i	distance from	X_{i-1} to X_i	measured along	Z_i
θ_i	angle between	X_{i-1} to X_i	measured about	Z_i

The position vector of a point of interest on the end-effector (any point or points of interest, where the student doctor can hold and move, such as the elbow) of a human articulated model can be written in terms of joint coordinates as $X = f(\theta)$ where $\theta = \{\theta_1 \ \cdots \ \theta_n\}^T \in R^n$ is the vector of n generalized joint coordinates defining the motion of a link with respect to its previous neighbor in the serial chain. The global position vector $X(\theta)$ can be obtained from the multiplication of the 4x4 homogeneous transformation matrices ${}^{i-1}_{\ \ i}T$, defined by the D-H representation method [1] as follows:

$$ {}^{i-1}_{\ \ i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1} d_i \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

The 4x4 transformation matrix ${}^0_iT$ used to represent i^{th} joint coordinate system with respect to the global base coordinate system {0} is:

$$ {}^0_iT(\theta) = {}^0_1T(\theta_1)\,{}^1_2T(\theta_2) \ldots {}^{i-1}_{\ \ i}T(\theta_i) \tag{2} $$

We use the augmented 4x1 vectors ${}^0_ir$ and ${}^i_ir$ to express the Cartesian coordinates of a point fixed in the i^{th} local frame in terms of the global coordinate system, respectively:

$$ {}^0_ir = \begin{bmatrix} X(\theta) \\ 1 \end{bmatrix} \qquad {}^i_ir = \begin{bmatrix} {}^iX \\ 1 \end{bmatrix} \tag{3} $$

where ${}^iX$ is the fixed point of interest on link i, expressed with respect to the i^{th} coordinate system. Using these relationships, ${}^0_ir$ can be written as:

$$ {}^0_ir = {}^0_iT(\theta)\,{}^i_ir \tag{4} $$

Given the set of joint angle θ, we can calculate the end-effector coordinates X. This is also called forward pose (position and orientation) kinematics, which is a straight-forward computation, $X = f(\theta)$. The Virtual Haptics Human Upper Body is focused on moving the end-effector in order to find all the joint angles. This procedure requires the solution of the inverse pose kinematics problem: $\theta = f^{-1}(X)$. Our Virtual Haptics Human Upper Body model consists of 71 degrees-of-freedom (DOF). The end-effector has six DOF (x,y,z,Rx,Ry,Rz). The system joint DOF is much greater than the end-effector Cartesian DOF. Our model is a hyper-redundant system. A redundant system has an infinite number of solutions for joint angles in the inverse pose kinematics problem.

In our case, we used Jacobian-based Inverse Kinematics to obtain the joint angles at every simulation step. This is an effective method to handle our hyper-redundancy with 71–6 = 65 redundant joint freedoms. The results yield surprisingly human-like motions. The following bullets describe a Jacobian matrix:

- A Jacobian is a vector derivative with respect to another vector, so it is a multi-dimensional form of the derivative.
- If we have a vector-valued function of a vector of variables $f(\theta)$, the Jacobian is a matrix of partial derivatives, with one partial derivative for each combination of components of the vectors (the rows represent the functions f and the columns indicate the variables θ).
- The Jacobian matrix thus contains all of the information necessary to relate a change in any component of f to a change in any component of θ.
- The Jacobian is usually written as $J(f,\theta)$, and it is generally represented as the matrix $[\partial f / \partial \theta]$:

$$ J(f,\theta) = \frac{\partial f}{\partial \theta} = \begin{bmatrix} \frac{\partial f_1}{\partial \theta_1} & \frac{\partial f_1}{\partial \theta_2} & \cdots & \frac{\partial f_1}{\partial \theta_n} \\ \frac{\partial f_2}{\partial \theta_1} & \frac{\partial f_2}{\partial \theta_2} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial f_m}{\partial \theta_1} & \cdots & \cdots & \frac{\partial f_m}{\partial \theta_n} \end{bmatrix} \tag{5} $$

where in our model m = 6 Cartesian DOF and n = 71 joint DOF. The Jacobian-based Inverse Kinematics can be expressed as:

$$ d\theta = J^{-1} dX \tag{6} $$

where:

dX is the change of the end-effector

$d\theta$ is the change of joint angles in the system

However, J^{-1} is not always obtainable. For a hyper-redundant system, J is not a square matrix and cannot be inverted. If we have a non-square matrix arising from a hyper-redundant system, we can instead use the underconstrained *pseudoinverse* (Williams 1994; Buss et al. 2004; Tolani et al. 2000):

$$ J^+ = (J^T J)^{-1} J^T \tag{7} $$

This is a method for finding a matrix that effectively inverts a non-square matrix. Our Virtual Haptics Human

Upper Body program uses Jacobian Inverse Kinematics to acquire the changes of joint angles in every simulation step according to $d\theta = J^{+}dX$. In the VHHUB program, the user can select up to two independent points (end effectors) to apply gross motion. Therefore, the size of the Jacobian matrix can be dynamically changed during simulation and our inverse kinematics algorithm accommodates the dynamic changing size of the Jacobian matrix.

4. VHHUB MODEL FEATURES

4.1 Dynamic Pivot Point

A unique feature of the VHHUB is a dynamic pivot point. For the human upper body, there is only small movement on the vertebrae close to the point where small amount of gross motion is applied. The dynamic pivot point feature enables our virtual model to dynamically move its pivot point during simulation. We model each virtual vertebra as a three degree of freedom joint (3 rotations.) This feature is to mimic the gross motion plapation technique (Figure 5.) It is shown the force induced side-bending for diagnose thoracic region. Different thoracic vertebrae movements can be produced depend on amount of shoulder movement. In Figure 5A, this technique produces most shoulder movement; therefore, the entire thoracic region (T1 – T12) will have movement. Figure 5B and Figure 5C can produce different amount of movement for diagnose T1- T8 (Figure 5B) or T1-T4 (Figure 5C.)

An example is shown in Figure 6. The top image indicates that only T1 through T4 are moving when user applies side bending left and T5 is the apex point. When any of the vertebra above apex point (T1-T4 in this example) reach their joint limit, our virtual model will free up the vertebra (T5) during next simulation step. In the bottom image of Figure 5, the vertebra in red (T4) has reached its joint limit and T6 become the new pivot point. This process will continue as another vertebra reaches its joint limit. This process was built into our inverse kinematics algorithm. The dynamic pivot point creates more natural and physiological virtual human upper body movements.

4.2 Deformable Skin

The next step is to attach deformable skin to our virtual human upper body for a realistic deformation according to the bone movement underneath the skin. This is critical to our haptics feel, enabling the student to feel realistic tissue texture changes due to motion of the virtual patient. A simple skinning technique (Lander 1998) is not adequate for a detail deformable model. By combining the smooth skinning technique (James and Twigg 2005) and skeletal-driven deformation (Lewis et al. 2000) we extended the concepts used in simple skinning and create more realistic deformable skin for our virtual model. Figure 7 shows that our skeletal structure model is covered with skin.

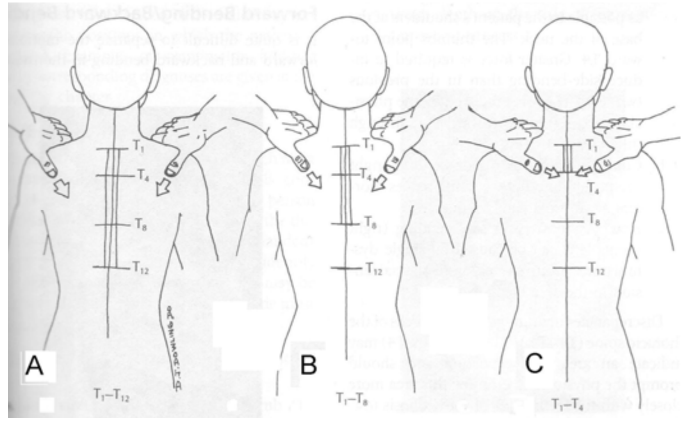


Figure 5. Localization of force induced for thoracic side-bending (from DiGiovanna 2005)

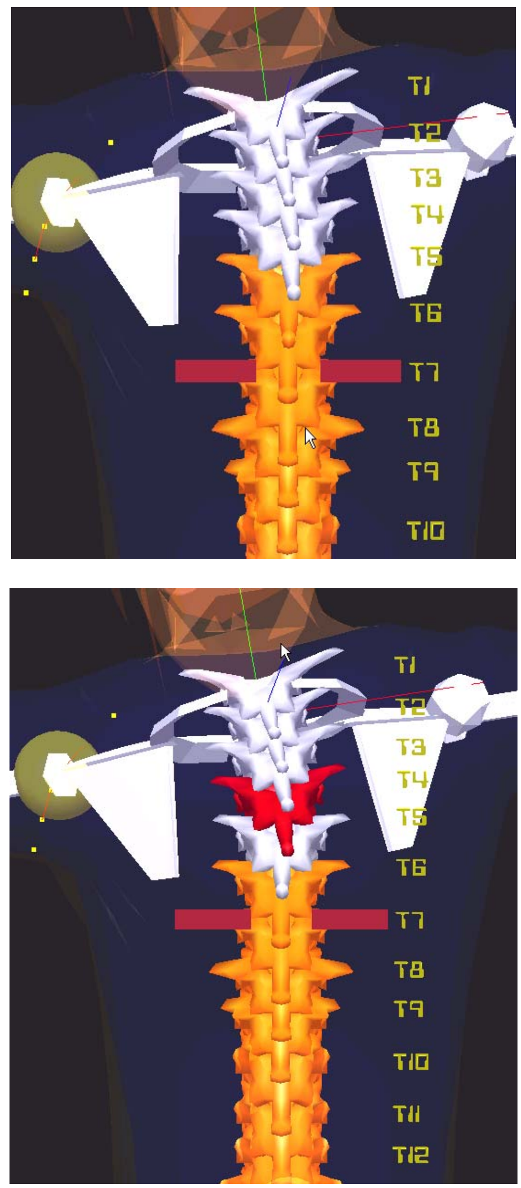


Figure 6. Dynamic Pivot Point

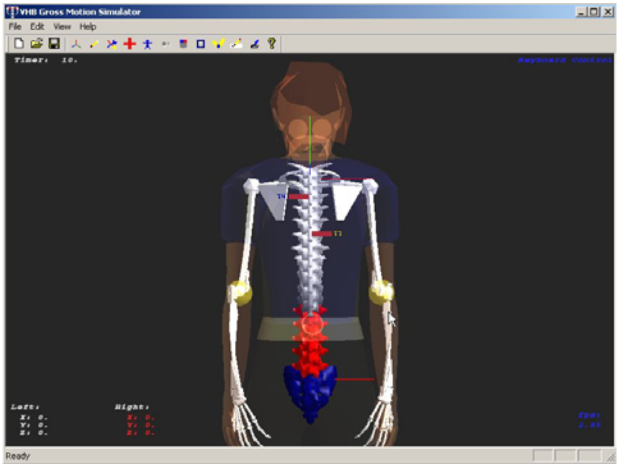


Figure 7. Skeleton with Skin: the Virtual Haptic Human Upper Body

Robots and simple characters made up from a collection of rigid components can be rendered through classical hierarchical rendering approaches (DeCoro and Rusinkiewiczy 2005; Teschner et al. 2005). Each component mesh is simply transformed into world space by the appropriate joint world matrix. This results in every vertex in the final rendered character being transformed by exactly one matrix.

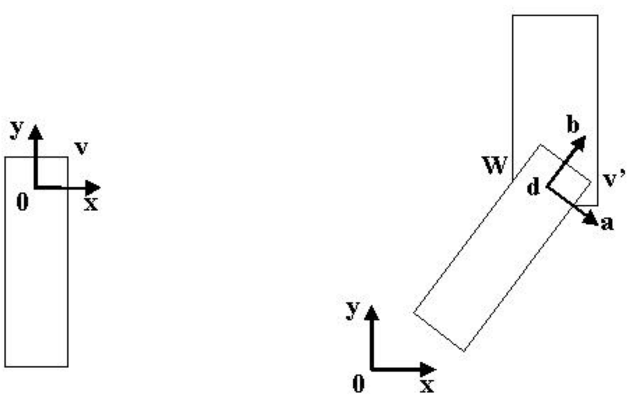
Expressed mathematically, we can say that for every vertex, we compute the world space position **v'** by transforming the local space position **v** by the appropriate joint world matrix **W**:

$$\mathbf{v}' = \mathbf{v} \cdot \mathbf{W} \tag{8}$$

where **W** is a 4x4 matrix and **v** is a 1x4 homogeneous position vector:

$$\mathbf{v} = \{v_x \quad v_y \quad v_z \quad 1\} \tag{9}$$

Every vertex in each mesh is transformed from the joint local space where it is defined into world space, where it can be used for further processing such as lighting and rendering. Vertex **v** defined in a joint's local space is shown in Figure 8a and vertex **v** transformed to world space using matrix **W** is shown in Figure 8b.



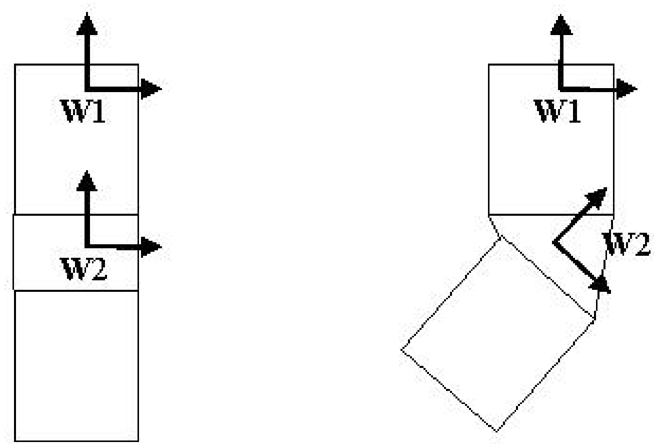
a. v in Local Joint Space **b. v in World Space**
Figure 8. Coordinate representations

Rendering with rigid components works just fine for robots, mechanical characters, and vehicles, but it is clearly not appropriate for organic characters with continuous skin.

With the *simple skinning* approach, the character's skin is modeled as a single continuous mesh. Every vertex in the mesh is attached to exactly one joint in the skeleton, and when the skeleton is posed, the vertices are transformed by their joint's world space matrix. As with the rigid component method, every vertex is transformed by exactly one matrix using an identical equation: $\mathbf{v}' = \mathbf{v} \cdot \mathbf{W}$. This implies that simple skinning should run about the same speed as rendering a character as rigid parts, and in practice, the two techniques often perform similarly with equal sized meshes.

The simple skinning technique is adequate for low detail models, but is clearly not sufficient for higher quality characters. In practice, the simple skinning algorithm can be made to work for characters with perhaps 500 or even as many as 1000 triangles, as long as care is taken in vertex placement and bone attachment. Simple skinning may be sufficient for lower detail characters, but for higher quality, it is too limited and a better solution is required.

Figure 9a shows an unbent knee with skin attached to joints 1 and 2. As shown in Figure 9b, every vertex is attached to exactly one joint, so as the knee bends, some distortion results.



a. Unbent Knee **b. Bent Knee**
Figure 9. Simple Deformation

Smooth skin extends the concepts used in simple skin. With smooth skinning, each vertex in the mesh can be attached to more than one joint, each attachment affecting the vertex with a different strength or *weight*. The final transformed vertex position is a weighted average of the initial position transformed by each of the attached joints. For example, the vertices in a character's knee could be partially weighted to both the hip joint (controlling the upper thigh) and knee joint (controlling the calf). Many vertices will only need to attach to one or two joints and rarely is it necessary to attach a vertex to more than four.

Using smooth skin, a vertex can be attached to more than one joint with and receive a weighted average of the transformations, as shown in Figure 10.

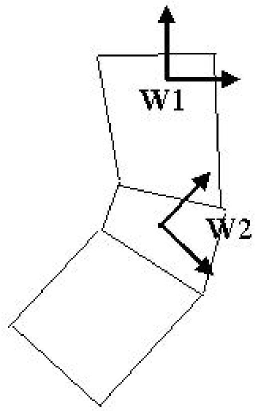


Figure 10. Vertex Attached to More Than One Joint

Let us say that a particular vertex is attached to N different joints. Each attachment is assigned a weight w_i which represents how much influence the joint will have on it. To ensure that no undesired scaling will occur, we enforce the constraint that all of the weights for a vertex must add up to exactly 1:

$$\sum_{i=0}^{N-1} w_i = w_0 + w_1 + w_2 + \cdots + w_{N-1} = 1 \tag{10}$$

To compute the world space position $\mathbf{v'}$ of the vertex, we transform it by each joint that it is attached to, and compute a weighted sum of the results:

$$\mathbf{v'} = \sum_{i=0}^{N-1} w_i \mathbf{v} \mathbf{B}_{[i]}^{-1} \mathbf{W}_{[i]} \tag{11}$$

where $\mathbf{v}$ is the untransformed vertex in *skin local space*, the space in which the skin mesh was originally modeled. The matrix $\mathbf{W}_{[i]}$ is the world matrix of the joint for attachment i. It is the result of the forward kinematics computations. We use the indexing notation $[i]$ to indicate that we don't want the matrix of the i^{th} joint in the skeleton (which would be written $\mathbf{W}_i$), but instead we want the world matrix of attachment i's joint. For example, if a particular vertex is weighted 60% to joint 37, 30% to joint 6, and 10% to joint 14, then we have $N = 3$ and:

$$\mathbf{W}_{[0]} = \mathbf{W}_{37} \qquad \mathbf{W}_{[1]} = \mathbf{W}_{6} \qquad \mathbf{W}_{[2]} = \mathbf{W}_{14} \tag{12}$$

$$w_0 = 0.6 \qquad w_1 = 0.3 \qquad w_2 = 0.1 \tag{13}$$

The matrix $\mathbf{B}_{[i]}$ is called the *binding matrix* for joint $[i]$. This matrix is a transformation from joint local space to skin local space, and so the inverse of this matrix, $\mathbf{B}_{[i]}^{-1}$, represents the opposite transformation from skin local space to joint local space. The combined transformation $\mathbf{B}_{[i]}^{-1}\mathbf{W}_{[i]}$ therefore first transforms $\mathbf{v}$ from skin local to joint local, then from joint local to world space. As the number of joints is likely to be small compared to the total number of vertices that need to be skinned, it is more efficient to compute $\mathbf{B}_{[i]}^{-1}\mathbf{W}_{[i]}$ for each joint before looping through all of the vertices. We will call this transform $\mathbf{M}_{[i]}$ defined by:

$$\mathbf{M}_{[i]} = \mathbf{B}_{[i]}^{-1}\mathbf{W}_{[i]} \tag{14}$$

The skinning equation that must be computed for each vertex then simplifies to:

$$\mathbf{v'} = \sum_{i=0}^{N-1} w_i \mathbf{v} \mathbf{M}_{[i]} \tag{15}$$

With the smooth algorithm, the attached skin reacts according to skeletal movement, as shown in Figure 11.

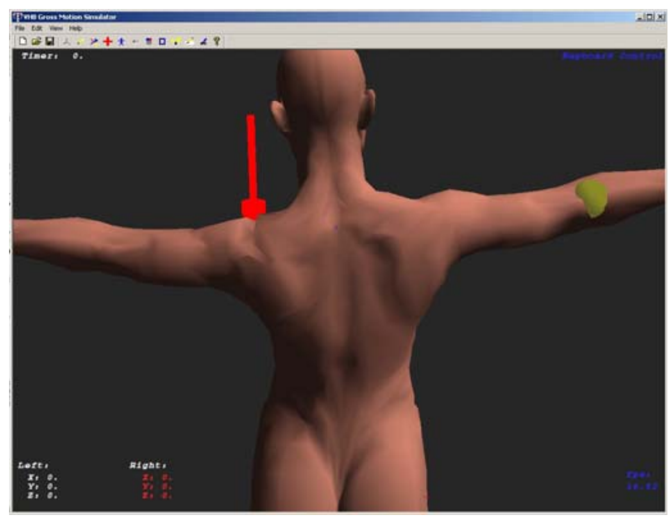


Figure 11. Deformed Skin with Gross Motion

4.3 Haptic Feedback

The main objective in creating the VHHUB is for medical students to practice feeling changes in human tissue texture due to motion testing. The OPEN HAPTICS® SDK (Software Development Kit) is the programming tool for the VHHUB model's haptic feedback.

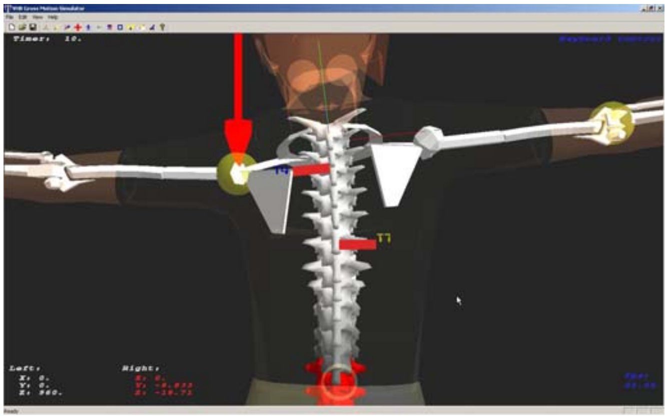


Figure 12. Simulated Upper Body Somatic Dysfunctions

In Figure 12, the red rectangles are examples of vertebra dysfunctions. They are on the surface right above the transverse process of the dysfunction vertebrae. Medical students have to identify the tissue compliance/stiffness change by touch in order to find the simulated problem. Those dysfunctions can be assigned in random locations within the spinal column, with varying degrees of subtlety. During the training, the transparency will be turned off for realistic diagnosis.

4.4 Family of Upper Body Models

We can create a family of VHHUB models to represent different patient populations, varying gender, body type, age, fitness, and other important aspects. Thus far we have created four VHHUB models two females (e.g. Figure 13) and two males with different body types. Different skin compliances are applied to the models, depending on measured surface compliances (Williams et al., 2007) of different human subjects.

Figure 13. VHHUB Petite Adult Female Model

4.5 Interaction Modes

During palpatory diagnosis tasks in the real world, osteopathic physicians use two primary modes of interaction for gross motion of the patient: active and passive. Under active control the patient moves according to physician verbal requests while the physician uses both hands for palpatory diagnosis of the resulting motions. Under passive control the patient relaxes while the physician controls the gross motion directly, leaving one hand for palpatory diagnosis of the resulting motions. Both modes have been programmed into the VHHUB. With active control, the virtual patient automatically responds to physician verbal requests as described in the following subsection. These active control motions start from three standard postures, programmed into VHHUB as shown in Figures 14 for the petite adult female model. All three postures are in common use in osteopathic clinical practice.

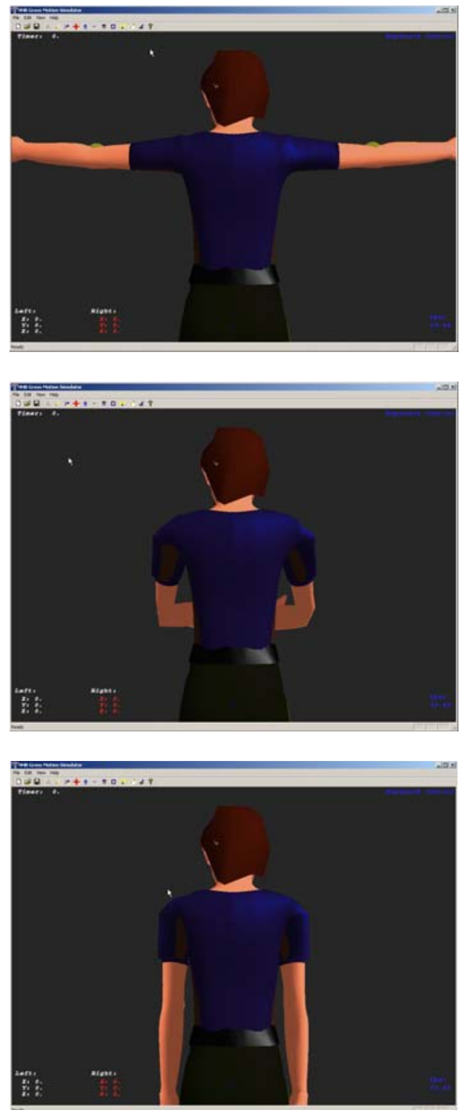


Figure 14. Three VHHUB Postures

With passive control, where the physician trainee must cause the motion, there are two options. First, the trainee can move the virtual patient directly by using a flight-stick-type haptic interface, after defining which portion of the body to interact with (such as either shoulder or elbow). Then the second haptic interface (a PHANToM OMNI from www.sensable.com) is used to perform the palpatory diagnosis, as shown in Figure 15.

Figure 15. Passive Control with Trainee Inputs

For the second passive control option, the trainee/user may define which point on the body should move, along with a 3D curve to define the desired motion. An example of this mode is shown in Figure 16.

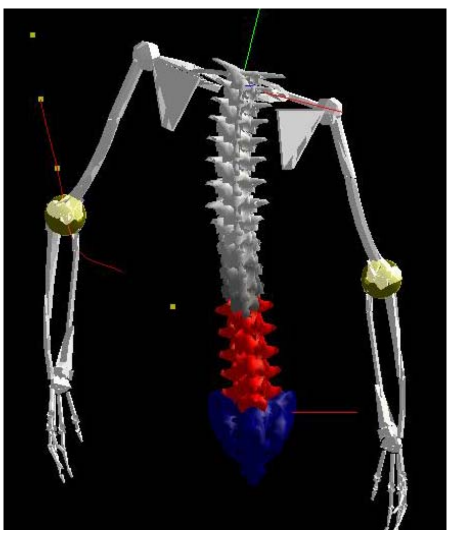


Figure 16. Passive Control with Elbow Following a User-Created Path

4.6 Voice Commands / Audio Feedback

In our VHHUB program, voice recognition and voice feedback technologies are implemented in addition to keyboard and haptic interface interaction. Voice commands can be given by the user to navigate the 3D environment (e.g. zoom in/out, turn on/off transparency). More importantly, voice input is used to give active motion commands (e.g. side bending left/right, rotation left/right, and flexion/extension) which activates the VHHUB model to perform gross motions without the force-feedback joystick input. This feature is to mimic when doctor ask patients to move by themselves, termed as active control in the above subsection. The main advantage of voice commands over the force-feedback joystick input is more degree of freedom input. For the force-feedback joystick, it has only two degree of freedom input to the end-effector. However, the voice command can give six degree of freedom input to the end-effector. Voice recognition technology looks for key words or complete sentence depending on the programming. For example, if user says “Please side bend to the left” or “Side bend left” then the virtual model will side bend to the left. “Side bend left” are the key words.

Another important feature is voice feedback from our virtual model. Voice feedback can be an additional hint (in addition to haptics) for the user to find somatic dysfunctions. For example, the user can ask our virtual patient “Where do you hurt?” or “How do you feel?” and the virtual model will have voice response (e.g. Doctor, my lower back hurts). This voice response can help the user to focus on zones in the virtual patient. There are endless possible dialogues which can be created for helping the user to improve their palpation techniques and support medical school curricula. In order to use voice recognition technology in the Microsoft Windows® environment, users must train the computer to recognize their voice.

4.7 Software Development

The primary programming language is C++. The OPENGL® API (Application Programming Interface) is used to create 3D graphics. The OPEN HAPTICS® SDK (Software Development Kit) is the programming tool for the VHHUB model’s haptic feedback. The finished software runs in a Microsoft Widows® environment.

4.8 Evaluation Plans

Realism is crucial to the VHHUB project and our philosophy. Osteopathic physicians and medical students are participating in two manners: up front, to give suggestions for programming and simulation from clinical practice, and to evaluate our resulting products, to validate the usability, realism, and osteopathic applicability of the movable VHHUB model.

Currently we are involved in concept development and data collection to ascertain how normal and abnormal human tissue should feel and change during gross motion tasks. We will collect skin compliance variations during gross motion palpation from human subjects in vivo. The collected data will be programmed into VHHUB to add more realism. This will be the first such objective research in osteopathy.

5. CONCLUSION

The Virtual Haptic Human Upper Body (VHHUB) is currently under development. The purpose is to generate automatic and realistic human motion for our Virtual Haptic Back (VHB) project, in which medical students are trained in their sense of touch for palpatory diagnoses. The user can apply side-bending, left- and right-rotation, and flexion and extension motions while using VHHUB. Combined motions are also enabled, though not commonly used clinically. This work is a major addition to our VHB product since it represents the first time our virtual human patient can move from the underlying skeletal structure, which changes the palpatory feel of vertebrae and soft tissues for more advanced clinical diagnoses. We incorporate forward and inverse pose kinematics solutions and user-selectable end-effector(s) from robotics into our model and simulation. Soft skin, pivot point and haptic feedback are also implemented. Another feature is multiple methods for creating virtual patient motion, including user-definable paths. This feature can be used for validating our model with biomechanical human data in the future.

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