The Virtual Haptic Human Upper Body for Palpatory Diagnostic Training

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Abstract

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Modern virtual medical simulators have many advantages over their manikin counterparts. For example, they are more repeatable and reconfigurable. The virtual reality can be upgraded and modified to serve different training purposes. The goal of the Virtual Haptic Human Upper Body (VHHUB) research is to create a physiologically-correct human upper body for osteopathic medical gross motion palpation training using haptics and virtual reality technologies. The virtual human upper body is a 71 degrees-of-freedom multiple end-effectors, multi-branching serial chain model. It has fully movable thoracic and lumbar spinal regions plus two shoulders and two arms with a deformable body. Due to the complexity of the VHHUB model, we present a velocity inverse kinematic problem solver with dynamic pivot point. This method ensures a smooth synchronization rate between graphics and haptic hardware in real time. Fryette’s principles are implemented in the VHHUB. Fryette’s principles are one of the fundamental theories for the osteopathic manipulative medicine (OMM) to diagnose somatic dysfunctions. The VHHUB software is developed in a way to help osteopathic physicians or OMM fellows fine tune the program for their student’s training. The haptic feedback of somatic dysfunctions can be modified by OMM faculty administrators without any knowledge of programming languages. The VHHUB provides an additional
training tool for the osteopathic medical students to augment their osteopathic manipulative medicine (OMM) laboratory courses. VHHUB evaluation and recommendations for future research are presented. From the preliminary evaluation data, most medical students gave 7 or up (scale from 1 to 10: 1 is unrealistic and 10 is realistic) on the realism of the VHHUB. Medical students also felt the simulation gave them a useful tool for learning Fryette’s principles.

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1. Introduction

1.1 Background

The Virtual Haptic Back (VHB) is one of the current research projects of the Interdisciplinary Institute for Neuromusculoskeletal Research at Ohio University, supported for five years by the Osteopathic Heritage Foundation (Williams et al. 2003). The current VHB is the first of its kind to apply haptics (force and touch feedback to the user) and VR (Virtual Reality) technology to support research and medical student training in the field of Osteopathic Medicine. Haptic devices give a human user the sense of touch and force from virtual computer models. The VHB hardware is shown in Figure 1.

![Figure 1: Virtual Haptic Back hardware installation](image)

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. Repeated 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. Evaluations have been conducted with osteopathic medicine students and continuous refinements of the VHB based on feedback from osteopathic physicians. However, the current VHB model is a static model. Users can only feel the surface stiffness and contour of the virtual back. In clinical situations, osteopathic physicians usually use dynamic palpation techniques to diagnose patients. One of the techniques is using gross motion of human upper body to create spine movements in order to find abnormally responding tissue. The focus of this research project is to create a user- movable Virtual Haptic Human Upper Body and incorporate it with haptics technology for training osteopathic medical students to use gross motion palpation techniques.

1.2 Introduction to Medical Simulations

Medical student’s clinical skills may not be sufficiently trained or practiced in an educational institution due to lack of faculty in a specialized area and/or lack of resources. Medical simulations can be used to help overcome these limitations. Medical simulations are widely used to teach or improve different clinical skills of medical students and professionals. The cost of the simulators depends on the complexity of the functions that are simulated. Even though a complex simulation experience including the necessary hardware, software and maintenance may be costly (e.g. more than $120,000 for the VHB hardware only, as shown in Figure 1), in the long term medical simulators could
help decrease the overall cost since they reduce medical errors (Lane et al. 2001). The key advantages of using simulation to help medical learning were summarized by Kneebone (2003):

1) The agenda and duration of the training depends on the learner, not the patient or subjects.

2) Learners have a chance to fail without consequences in a safe, simulated environment. Learner can explore and practice to the limits of the technique without safety issues.

3) The simulations can be used for more objective assessments and as a learning-performance measurement tool since the data can be collected automatically and analyzed,

4) They can provide learners with immediate performance feedback.

Medical education simulations incorporating haptics have increased in recent years due to the improvement of haptic devices. We present a brief literature review of two recent haptic medical simulations to give a general idea of how haptics have been implemented and improve the realism and efficiencies of simulators.

Niemeyer et al. (2004) developed a surgical simulator for telerobotic surgery. The Two-Handed Universal Master Project (THUMP) allowed them to develop and construct a surgical training console (Figure 2).
There are two subsystems (master and slave). The master system is a haptics enabled console at the trainee site. The slave system is at the surgical site. Sitting at the THUMP console, the operator views real or virtual images of the surgical site in the stereoscopic goggles, providing an immersive, three dimensional environment. The virtual master subsystem is for the expert to monitor the operator’s surgical procedures. Its two-handed haptic capabilities can provide force and torque feedback cues identical to those experienced during the actual procedures (Figure 3). The THUMP console provides an important new test-bed for telerobotic surgical training.
Aloisio et al. (2005) developed a simulator for coronary stent implantation. A stent is a permanent implant that is used to open a coronary artery and to keep it open. They used a HERMES (HEmatology Research virtual MEdical System) haptic interface (Figure 4) which allows the user to interactively navigate within a reconstructed artery. Force feedback is produced when contact occurs between the artery walls and the medical instruments. Both visual (Figure 5) and haptic feedback were provided for the interaction of the surgical tools in the virtual environment.
From those medical simulators, it shown that the haptic technology incorporated with virtual reality can help the medical students improving their clinical skill. In order to achieve a realistic human upper body motions, the inverse kinematics algorithm is
established for our virtual human upper body skeletal system. The following subsection is a review of popular methods for solving inverse kinematics problem.

1.3 Review of Inverse Kinematics

Solving the inverse kinematics problem of the virtual haptic human upper body skeletal system is one of the essential steps of implementation of gross motion for our virtual moveable human upper body. Inverse kinematics in robotics terms is a mathematical method to find the joint angles (dependent on the degree of freedom of the robot system) as a result of motion of the end effector(s). Many mathematical methods can be used to solve inverse kinematics. We will introduce some of the most common methods as used by robotics researchers and 3D game creators. The Cyclic Coordinate Descent (CCD) is a well-known algorithm used for inverse kinematics solutions in applications involving joint-chains (Ramakrishnan 2008). CCD is a heuristic approach that uses the greedy paradigm. The CCD algorithm for an n-link chain as shown in Figure 6, with the following notations:

- \((x_T, y_T)\) : Position of the target
- \((x_E, y_E)\) : Position of the end-effector
- \((x_i, y_i)\) : Pivot point of the ith link, \(i = 1, 2, \ldots, n\)
- \(t_i\) : Target vector for the ith link = \((x_T - x_i, y_T - y_i)\)
- \(e_i\) : End-effector vector for the ith link = \((x_E - x_i, y_E - y_i)\)
- \(\alpha_i\) : Angle between vectors \(t_i\) and \(e_i\).
The CCD algorithm can be summarized as follows (Ramakrishnan 2008):

1. Set $i = n$.
2. Compute $\alpha_i$
3. Rotate the $i$th link by angle $\alpha_i$ so that the end-effector meets the target vector $t_i$.
4. Decrement $i$, and go to step 2 if $i > 0$.
5. Repeat steps 1 to 4 until target position is reached.

The CCD method is simple and easy to implement. However, it has several drawbacks such as the requirement for a number of iterations for certain configurations, and unnatural joint angle rotations performed for certain target positions. The CCD method takes a local approach to solve the inverse kinematics. It is difficult to implement global constraints such as equality constraints between several joints.

The second method we would like to introduce is the Jacobian Inverse method. The Jacobian Inverse method is also popular for solving inverse kinematics (Chen et al. 2009a; Šoch et al. 2005; Schwartz et al. 2003). The basic concept of the Jacobian Inverse method is as follows:
We have $y_0 = f(x_0)$ where $y_0$ is the current end effector position and $x_0$ is the current parameter vector.

We would like to solve $y_1 = f(x_0 + \Delta x)$ where $y_1$ is the desired end effector position and $\Delta x$ is the unknown modification to $x_0$ which will satisfy $y_1$.

We take a Taylor expansion of the function $y_1 = f(x_0 + \Delta x)$:

$$y_1 = f(x_0) + \frac{\partial f(x_0)}{\partial x} \Delta x + o(||\Delta x||^2)$$

Since $f(x)$ is a vector function, $\frac{\partial f}{\partial x}$ is a matrix of first order partial derivatives. Such a matrix is usually denoted $J$ (the Jacobian matrix) so ignoring the higher-order terms we can shorten the expression to:

$$y_1 = f(x_0) + J(x_0)\Delta x$$

Since $y_0$ is the solution to $f(x_0)$, we can find $\Delta x$:

$$\Delta x = J^{-1}(x_0)(y_1 - y_0)$$

Therefore we can find the new configuration.

In contrast to the CCD method, the Jacobian Inverse method solves inverse kinematics globally and can be applied constrains to individual joints (Chen and Williams 2009a). One great advantage of the Jacobian inverse is, that it minimizes the work done, in the sense that any given solution is a minimum change solution, compared to the previous iteration. This gives a more fluid motion without the erratic discontinuities of the CCD method. For these reasons, we chose the Jacobian Inverse method for solving our virtual haptic human upper body skeletal system inverse kinematics.
The Jacobian Inverse method, however, has its own problems. This method requires the inversion of a matrix that might be singular; it might not even be a square matrix. We overcome the inversion of non-square matrix by using *pseudoinverse* (Buss et al. 2004; Tolani et al. 2000; Williams 1994). The implementation details are presented in Section 2.

There are still other methods to solve the inverse kinematics problem. Wu et al. (2004) proposed an analytical method in order to solve a 12 degree-of-freedom human model. They divided the human model into different zones and solved inverse kinematics within the zones. Each zone cannot have degrees-of-freedom greater than 7 because of the closed form solutions they used. Constraints can be applied to each zone but not globally. In a similar approach for solving human postures with inverse kinematics, Kallmann (2007) used pre-designed key body postures (Figure 7), which are organized as a function of the direction to the goal to be reached and solve inverse kinematics according to different part of body. These methods are only useful for specific types of human motions.
Kulpa et al. (2005) used a hybrid approach to develop an algorithm to solve human postures inverse kinematics. They subdivided the human body into kinematic subchains and solved individual chains using the CCD method. They also use the center of mass of as a measure factor to verify that the correct posture was reached. Their algorithm improved the CCD method by decomposing the body into groups. If the solution can be reached by only using one group, a unique calculation is carried-out. Consequently, it avoids the multiple iterations needed by the CCD method.

We have introduced several popular methods for solving inverse kinematics problem in this section. Most of the approaches were specifically related to human postures. However, these human models all used simplified skeletal systems. A review of current virtual human research that use more complex models will be presented next.
1.4 Review of current Virtual Human Research

Most virtual human research focuses on workspace and obstacle avoidance analyses. Human limbs are considered as the end-effectors. The majority of virtual human research is focused on the results of the end-effectors (Human Limbs) movement. For example a research group in University of Iowa simulated a virtual human upper body by using an optimization control method. Part of their virtual model is shown in Figure 8. It is clear that they focus on the limb movements. There is only six degrees-of-freedom for the spinal column. They minimized cost functions (i.e. potential energy) to obtain arm trajectories and used control points to achieve smooth limb movements and to avoid obstacles (Abdel-Malek et al. 2004). Their algorithm is different from the traditional inverse kinematics method. Due to the complexity of calculations, it is difficult to achieve real-time simulation with their algorithm. For our virtual human upper body, we incorporate haptic devices in our virtual simulation. A smooth sync rate between graphics and haptic hardware is essential. A fast inverse kinematics solving algorithm is required.
Hodgins et al. (1995) simulated dynamic athletic movements. They simulated athletes running, bicycling, and vaulting by using control algorithms. In Figure 9, a virtual athlete model is shown.
From Figure 9, there was no spinal column movement modeled. They used control algorithms to obtain desire 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 limited to limb movements.

Maurel and Thalmann (2000) used work space constraints to simulate virtual human shoulder movements (Figure 10).
They implemented a traditional inverse kinematics method to find the joint angles during shoulder motions and added work-space constraints to achieve natural human shoulder movements (Maurel and Thalmann 2000). While, their analysis was limited to part of the human upper body, their algorithm was able to achieve more accurate, local skeletal movements.

All of the above virtual human studies were aimed at simulation of natural human limb movements and work spaces. The goal of Virtual Haptic Human Upper Body is to:

“Develop a physiologically correct virtual moveable human upper body incorporating haptics feedback technology to train osteopathic medical students to be able to recognize normal and abnormal vertebral motion of the human spine using gross motion diagnosis techniques.”

The Virtual Haptic Human Upper Body focuses on individual vertebral movement rather than limb work space. However, individual bone movements are still the result of
end-effectors (limbs) movement. The intermediate joint angles of the virtual human upper body model need to be calculated in real time. In next section, modeling the Virtual Haptic Human Upper Body will be discussed in detail which includes modeling the skeletal system and deformable skin.
2. Modeling the Virtual Haptic Human Upper Body

2.1 Movable Skeletal System

The first step is to develop an appropriate movable skeletal system for the Virtual Haptic Human Upper Body (VHHUB). The human skeleton can be considered as a series of connected rotational links. The VHHUB specifically focuses on the thoracic vertebrae (T1 to T12) as shown in Figure 11, the lumbar vertebrae (L1 to L5) (Figure 11), the shoulders (Figure 12) and the two arms.

![Anatomy of a Human Spine](image)

*Figure 11: Anatomy of a Human Spine (Anatomy 2006)*

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

Figure 12: A 3D Human Shoulder Model

The skeletal system of the virtual human upper body is shown in Figure 13.

Figure 13: The Skeletal System of the Virtual Human Upper Body
Consider Figure 14 where two consecutive joints are shown.

The four DH parameters (depicted in Figure 14) are:

- \( a_i \) is the distance from \( Z_{i-1} \) to \( Z_i \) measured along \( X_i \);
- \( \alpha_i \) is the angle between \( Z_{i-1} \) and \( Z_i \) measured about \( X_i \);
- \( d_i \) is the distance from \( X_{i-1} \) to \( X_i \) measured along \( Z_i \); and
- \( \theta_i \) is the angle between \( X_{i-1} \) to \( X_i \) measured about \( Z_i \).

A complete list of DH parameters of the virtual human upper body is in Appendix A. The position vector of a point of interest on the end-effector of a human articulated model can be written in terms of joint coordinates as
where $\theta[\theta_1...\theta_n]^T \in R^n$ is the vector of n generalized joint coordinates defining the motion of a link with respect to another. The global position vector $X(\theta)$ can be obtained from the multiplication of the 4x4 homogeneous transformation matrices $i^{-1}T_i$, defined by the Denavit-Hartenberg (DH) representation method (Denavit and Hartenberg) (Craig 2005) as follows:

$$X = X(\theta) \quad (1)$$

$$i^{-1}T_i = \begin{bmatrix}
\cos(\theta_i) & -\sin(\theta_i) & 0 & a_{i-1} \\
\sin(\theta_i)\cos(\alpha_{i-1}) & \cos(\theta_i)\cos(\alpha_{i-1}) & -\sin(\alpha_{i-1}) & -\sin(\alpha_{i-1})d_i \\
\sin(\theta_i)\sin(\alpha_{i-1}) & \cos(\theta_i)\sin(\alpha_{i-1}) & \cos(\alpha_{i-1}) & \cos(\alpha_{i-1})d_i \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (2)$$

The 4x4 homogeneous transformation matrices $i^{-1}T_i$ can also be expressed as:

$$i^{-1}T_i = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} \quad (3)$$

where $R$ is a 3 x 3 rotation matrix and $d$ is a 3 x 1 position vector.

The 4x4 transformation matrix $0^iT_0$ used to represent $i^{th}$ joint coordinate system with respect to the global base coordinate system $\{0\}$ is

$$0^iT_0(\theta) = 0^iT_0(\theta_1)^*T_2(\theta_2)...i^{-1}T_i(\theta_i) \quad (4)$$

We use the augmented 4x1 vector $0^i_r$ and $i^r_r$ to express the Cartesian coordinates of the point fixed in the $i^{th}$ local frame in terms of global local coordinate system, respectively:
\[ ^0r = \begin{bmatrix} X(\theta) \\ 1 \end{bmatrix} ; \quad ^i r = \begin{bmatrix} ^i X \\ 1 \end{bmatrix} \quad (5) \]

where \(^i X\) is the fixed point of link \(i\) and is expressed with respect to the \(i^{th}\) coordinate system. Using these relationships, \(^0r\) can be written as:

\[ ^0r = ^0T(\theta)^{i_1}r \quad (6) \]

We can find the end-effector coordinates from the given joint angles.

\[ \bar{X} = F(\bar{\theta}) \quad (7) \]

or

\[
\begin{align*}
x1 &= f_1(\theta_1, \theta_2, \theta_3, \ldots, \theta_n) \\
x2 &= f_2(\theta_1, \theta_2, \theta_3, \ldots, \theta_n) \\
x3 &= f_3(\theta_1, \theta_2, \theta_3, \ldots, \theta_n) \\
x4 &= f_4(\theta_1, \theta_2, \theta_3, \ldots, \theta_n) \\
x5 &= f_5(\theta_1, \theta_2, \theta_3, \ldots, \theta_n) \\
x6 &= f_6(\theta_1, \theta_2, \theta_3, \ldots, \theta_n) 
\end{align*} \quad (8) \]

\(\bar{X}\) has three position \((x1, x2, x3)\) components and three rotation \((x4, x5, x6)\) components.

This is the forward kinematics problem solution.
The Virtual Haptic Human Upper Body model is focused on moving the end-effector(s) and finding all the joint angles. This is called the inverse kinematics problem:

\[ \hat{\theta} = F^{-1}(\hat{X}) \]  

(9)

Our Virtual Haptic Human Upper Body model consists of 71 degrees of freedom (DOF). One end-effector has six degree of freedom(x,y,z,Rx,Ry,Rz). The system’s DOF is much greater than the end-effector’s DOF so our model is a hyper redundant system. A redundant system has infinite number of solutions for joint angles. In our case, we use the rate-based Jacobian Inverse Kinematics to obtain the joint angles at every simulation step.

What is a Jacobian?

- A Jacobian is a vector derivative with respect to another vector
- If we have a vector valued function of a vector of variables \( F(\hat{\theta}) \) (equation 8), the Jacobian is a matrix of partial derivatives, one partial derivative for each combination of components of the vectors
- The Jacobian matrix contains all of the information necessary to relate a change in any component of \( \theta \) to a change in any component of \( F(\hat{\theta}) \)
- The Jacobian is usually written as \( J(F, \theta) \), but one can think of it as \( df/d\theta \)
$$J(F, \theta) = \frac{dF}{d\theta} = \begin{bmatrix} \frac{\partial f_1}{\partial \theta_1} & \frac{\partial f_1}{\partial \theta_2} & \cdots & \frac{\partial f_1}{\partial \theta_N} \\ \frac{\partial f_2}{\partial \theta_1} & \frac{\partial f_2}{\partial \theta_2} & \cdots & \frac{\partial f_2}{\partial \theta_N} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_M}{\partial \theta_1} & \frac{\partial f_M}{\partial \theta_2} & \cdots & \frac{\partial f_M}{\partial \theta_N} \end{bmatrix}$$

(10)

$J$ is the Jacobian matrix. The relation between the linear and angular velocity of the end-effector and the vector of joint velocities (Spong and Vidyasagar 1989):

$$\begin{bmatrix} 0_v \\ 0_\omega \end{bmatrix} = J \dot{\theta}$$

(11)

where $0_v$ is the linear velocity of the end-effector. $0_\omega$ is the angular velocity of the end-effector. $J$ can be written as:

$$J = \begin{bmatrix} J_v \\ J_\omega \end{bmatrix}$$

(12)

where $J_v$ and $J_\omega$ are 3 x n matrices. Note that $J$ is a 6 x n matrix for one end-effector where n is the number of joints. For two end-effectors, $J$ is a 12 x n matrix because there are 6 degrees-of-freedom for each end-effector. The two end-effectors are coupled with the spinal column.

The upper half of the Jacobian matrix $J_v$ is given as:

$$J_v = [J_{v1} \ldots J_{vn}]$$

(13)

where the i-th column of $J_{vi}$ is:

$$J_{vi} = z_i \times (o_n - o_i)$$

(14)

if joint i is revolute and

$$J_{vi} = z_i$$

(15)

if joint i is prismatic.
In equation 14 and equation 15:
\[ z_i = ^0_i R K, \quad z_0 = K = (0,0,1)^T \]  
(16)
\[ o_n - o_i = ^0_i R d^i_n \]  
(17)
where \(^0_R\) is a 3 x 3 orthonormal rotation matrix giving the orientation of \(\{i\}\) with respect to \(\{0\}\) and \(d^i_n\) is the position vector from the origin of \(o_i\) to the origin of \(o_n\) expressed in \(\{1-1\}\) coordinates.

The lower half of the Jacobian matrix \(J_\omega\) is given as:
\[ J_\omega = [\rho_1 z_0 \ldots \rho_n z_n] \]  
(18)
where \(\rho_i\) is equal to 1 if joint \(i\) is revolute and \(\rho_i\) is equal to 0 if joint \(i\) is prismatic (with no rotation).

The detailed derivation of \(J_\rho\) and \(J_\omega\) is shown in Appendix B.

The Jacobian Inverse Kinematics problem can be derived as:
\[ d\tilde{\theta} = J^{-1} d\tilde{X} \]  
(19)
\(d\tilde{X}\) is the change of position and rotation of the end-effector.
\(d\tilde{\theta}\) is the change of joint angles in the system.

However, \(J^{-1}\) is not always obtainable. For a hyper redundant system, matrix \(J\) is not a square matrix and cannot be inverted.

If we have a non-square matrix arising from a hyper redundant system, we used the underconstrained Moore-Penrose pseudoinverse (Buss et al. 2004; Tolani et al. 2000; Williams 1994):
\[ J^+ = J^T (J J^T)^{-1} \]  
(20)
This is a method for finding a matrix that effectively inverts a non-square matrix. Out of the infinite possible solutions, this underconstrained Jacobian matrix pseudoinverse chooses the solution with the minimum joint rate norm. The Virtual Haptics Human Upper Body program uses Jacobian inverse kinematics to acquire the changes of joint angles in every simulation step. In the Virtual Haptics Human Upper Body program, a user can select up to two independent end-effector points to apply gross motions. Therefore, the size of the Jacobian matrix can be dynamically changed during simulation. Our inverse kinematics algorithm can accommodate changing size of the Jacobian matrix in real-time.

2.2 Dynamic Pivot Point

A unique feature of the VHHUB is the dynamic pivot point. This is the first movable vertebra closest to the sacrum (base frame) in the serial joint chain can dynamically change base (i.e. from T7 to T8) as a result of a large amount of movement of the end-effector. For the virtual human upper body, there is only a small movement of the vertebrae that are close to the point where a 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 degrees of freedom joint (3 axis of rotations). The dynamic pivot point feature allows one to mimic the gross motion palpation technique. In Figure 15 the force used to induce side-bending is shown. Different thoracic vertebrae movements can be produced depending on the amount of shoulder movement. In Figure 15A, sufficient force is applied to produce vertebral
movements throughout the thorax (T1 – T12). In Figure 15B and Figure 15C different amounts of force produce different amounts of movement in the vertebral column.

An example is shown in Figure 16. The left image indicates that only T1 through T4 are moving when the user applies side bending left and T5 is the pivot point. When any of the vertebrae above the pivot point (T1-T4 in this example) reach their joint limit or any feasible thresh hold established by the VHHUB administrator, our virtual model will free up vertebra (T5) during the next simulation step. In the right image of Figure 16, the vertebra in red (T4) has reached its joint limit and T6 becomes the new pivot point. This process will continue as another vertebra reaches its joint limit or thresh hold. This process was built into our inverse kinematics algorithm. The dynamic pivot point feature can reduce calculation time of solving the inverse kinematics problem when there is a small movement of the end-effector. For example when the dynamic pivot point feature is turned off, the calculation process has to invert a 6 x 71 Jacobian matrix (for one end-effector). When this feature is turned on, if T5 is the pivot point, the calculation process only has to invert a 6 x 35 Jacobian instead. The size of the Jacobian matrix is dynamically changed during the simulation when the dynamic pivot point feature is turned on. The dynamic pivot point creates more natural and physiological virtual human upper body movements.
2.3 Deformable Skin

The next step is to attach deformable skin to our virtual human upper body for a realistic deformation according to the skeletal movement underneath the skin. This is
critical to our future haptics feel, enabling the student to feel realistic tissue texture changes due to motion of the virtual patient. A simple skinning technique (Lander 1998; Rotenberg 2005) is not adequate for a detailed deformable model. By combining a simple skinning technique with the smooth skinning technique (James and Twigg, 2005; Rotenberg 2005), we will extend the concepts used in simple skinning and create more realistic deformable skin for our virtual model.

The basic element of a 3D model is a vertex (a 3D point). Vertices construct skin meshes (surfaces) of a 3D model. We can calculate every skin vertex’s position in respect to the base frame in our 3D human upper body model by using equation 21. In equation 21 we compute the world space position of vertex \( v \) by multiply the vertex local space position \( v \) by joint world transformation matrix \( W \) (Rotenberg 2005):

\[
v' = v \cdot W
\]  

(21)

where \( W \) is a 4x4 matrix and \( v \) is a 1x4 homogeneous position vector:

\[
v = \begin{bmatrix} v_x & v_y & v_z & 1 \end{bmatrix}
\]  

(22)

The new world space position of every vertex in each mesh can be used to process the changes of lighting and rendering of our virtual human upper body model. Figure 17a (Rotenberg 2005) shows vertex \( v \) in a joint’s local space and vertex \( v \) in respect to the base frame after transformed by using world transformation matrix \( W \) is shown in Figure
17b (Rotenberg 2005). This *simple skinning* technique is sufficient to simulate rigid bodies (robots, machines, and vehicles) but apparently not adequate for characters with soft skin.

![Coordinate Representations](image)

**Figure 17: Coordinate Representations (Rotenberg 2005)**

The skin attached to the joint(s) of a rigid body model is modeled as a single continuous mesh for each joint. The joint skin vertices are attached to only the joint which the skin covered. When a joint or joints in the skeleton move, the skin vertices are transformed by using equation 21. As with *simple skinning* technique, every vertex is transformed by exactly one world transformation matrix using equation 21. The *simple skinning* technique process approximately the same speed as rendering a character without skin.

The *simple skinning* technique is suitable for low detail or rigid models, but is obviously insufficient for higher detail characters with soft skin. “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.” (Rotenberg 2005) Figure 18a (Rotenberg 2005) shows an unbent knee with skin attached to joints 1 and 2. As shown in Figure 18b (Rotenberg 2005), every vertex is attached to precisely one joint; as the knee bends some distortion results.

![Unbent Knee](image1) ![Bent Knee](image2)

*Figure 18: Simple Deformation (Rotenberg 2005)*

In order to simulate soft body deformation of our virtual haptic human upper body the *Smooth skinning* technique (Rotenberg 2005) is implemented. The difference between the *simple skinning* technique and *Smooth skinning* technique is the skin mesh vertex can be attached to multiple joints using *Smooth skinning* technique. There is a weighted average which is assigned to each of the attached joint to mark the influence of a joint to the skin vertex. The world coordinates of the skin vertex is the sum of weighted average of the initial position transformed by each of the attached joints.
With Smooth skinning technique, a skin vertex can be attached to more than one joint and form a weighted average of the transformations, as shown in Figure 19 (Rotenberg 2005). In equation 23, a weight $w_i$ is assigned to each of the $N$ different joints which a skin vertex is attached to.

$$\sum w_i = 1 = w_0 + w_1 + \cdots + w_n$$  \hspace{1cm} (23)

The sum of all $w_i$ must be equal to 1 to prevent the unwanted graphic scaling problem (Rotenberg 2005):

Equation 24 shows the computation of the skin vertex world space position $\mathbf{v}'$, the local space coordinate of a skin vertex is transformed by each joint that the skin vertex is attached to, and the results as follows (Rotenberg 2005):

$$\mathbf{v}' = \sum w_i \mathbf{v} \cdot \mathbf{B}_{i}^{-1} \cdot \mathbf{W}_{i}$$  \hspace{1cm} (24)
where \( \mathbf{v} \) is the skin vertex in *skin local space* before transformation. The world transformation matrix of the joint \([i]\) is \( \mathbf{W}_i \). It can be obtained through the forward kinematics computations. The index \([i]\) represents the \(i\)'s joint which the skin vertex attached to. It is not the \(i^{th}\) joint in the skeleton. For example, if a skin vertex is weighted 50\% to joint #24, 40\% to joint #3, and 10\% to joint #10, then we have:

\[
N=3, \quad \mathbf{W}_{[0]} = \mathbf{W}_{24}, \quad \mathbf{W}_{[1]} = \mathbf{W}_{3} \quad \text{and} \quad \mathbf{W}_{[2]} = \mathbf{W}_{10} \quad (25)
\]

\[
w_0 = 0.5, \quad w_1 = 0.4 \quad \text{and} \quad w_2 = 0.1
\]

The matrix \( \mathbf{B}_{[i]} \) is called the *binding matrix* (Rotenberg 2005) for joint \([i]\). The matrix \( \mathbf{B}_{[i]} \) is the transformation matrix from joint local space to skin local space. The inverse of this transformation matrix, \( \mathbf{B}_{[i]}^{-1} \), is the transformation from skin local space to joint local space.

In equation 24, \( \mathbf{B}_{[i]}^{-1} \cdot \mathbf{W}_{[i]} \) transform the skin vertex \( \mathbf{v} \) from skin local space to joint local space, then from joint local to world space. The number of joints in the skeleton is far less than the number of skin vertices in the skin mesh. We can pre compute \( \mathbf{B}_{[i]}^{-1} \cdot \mathbf{W}_{[i]} \) for each joint which the skin vertex attached to before going through all of the vertices computation. This transformation matrix \( \mathbf{M}_{[i]} \) is defined by (Rotenberg 2005):

\[
\mathbf{M}_{[i]} = \mathbf{B}_{[i]}^{-1} \cdot \mathbf{W}_{[i]} \quad (26)
\]

The *smooth skinning* equation (equation 24) that has to be calculated for each skin vertex and can be simplified to

\[
\mathbf{v}' = \sum w_i \mathbf{v} \cdot \mathbf{M}_{[i]} \quad (27)
\]
With the smooth skinning algorithm, the attached skin can react according to the bone movement, as shown in Figure 20.

![Figure 20: An example of deformed skin with gross motion applied](image)

Modeling procedures of the VHHUB and a comparison of other virtual human modeling procedure are summarized in Table 1.
Table 1: Summary of the VHHUB modeling procedures

<table>
<thead>
<tr>
<th>Modeling Procedures</th>
<th>VHHUB Approach</th>
<th>Popular or Conventional Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal system</td>
<td>Detailed spinal column</td>
<td>Less detailed or no spinal column</td>
</tr>
<tr>
<td>Joint coordinates representation</td>
<td>D-H representation</td>
<td>D-H representation</td>
</tr>
<tr>
<td>Inverse kinematics solver</td>
<td>Jacobian inverse kinematic solver with dynamic pivot point</td>
<td>CCD, optimal control and Jacobian inverse kinematics solver</td>
</tr>
<tr>
<td>Deformable soft body</td>
<td>Smooth Skinning</td>
<td>Simple or Smooth Skinning</td>
</tr>
</tbody>
</table>

After modeling the movable skeletal system and deformable body, the hardware setup for the Virtual Haptic Human Upper Body will be presented in the next section.

The VHHUB software can run on either a laboratory hardware configuration or a mobile hardware configuration. The mobile hardware configuration can be transported easily and the cost of the equipment is less. Both configurations have their advantages and disadvantages. A detailed discussion will be in the following session.
3. **Hardware Setup**

The VHHUB is using a Microsoft Sidewinder® Force-Feedback joystick (Figure 21) to move the end-effector (point of interest) of our Virtual Haptics Human Upper Body. However, the user has the ability to move the end-effector either by a Microsoft Sidewinder® Force-Feedback joystick or by using voice commands (Section 4). We have also adapted a SensAble Omni® (Figure 22) to be used for haptic feedback of the spinal processes and soft tissues in a mobile unit. We also use a SensAble PHANTom 3.0® (Figure 23) instead of the SensAble Omni® as a desktop setup which can generate more force feedback and better haptic resolution. The detailed hardware configurations are shown as follows.

*Figure 21: Microsoft Sidewinder® Force-Feedback joystick*
3.1 Haptic Device for Gross Motion Input

The Microsoft Sidewinder® Force-Feedback joystick is our choice of haptic device to apply gross motion. A custom-made stand is used to mount the joystick.
vertically (Figure 24) to mimic how the gross motion is induced in clinical palpatory examinations.

*Figure 24: Joystick Vertical Stand*

Figures 25 through 31 show the input from the joystick and output to the virtual patient.

*Figure 25: Joystick Input creates side-bending left*
When a user pushes the joystick downward, it creates a side-bending left motion to the virtual patient (Figure 25).

*Figure 26: Joystick Input creates side bending right*

When a user pushes the joystick upward, it creates a side-bending right motion to the virtual patient (Figure 26).
When a user pushes the joystick forward, it creates a rotation right motion to the virtual patient (Figure 27). In Figure 28, a user pushes the joystick backward and creates a rotation left motion to the virtual patient.

Figure 27: Joystick Input creates rotation right

Figure 28: Joystick Input creates rotation left
When a user presses and holds the number one button (Figure 29) of the joystick while pushing forward, it creates a flexion motion to the virtual patient (Figure 30). When a user presses and holds the number one button of the joystick while pushing backward, it creates an extension motion to the virtual patient (Figure 31).

*Figure 29: Joystick button number one*

*Figure 30: Joystick Input creates flexion motion*
In this Subsection, we described the available gross motion inputs from the haptic joystick. However, side bending and rotation motions can be combined using the haptic joystick, for example, a user pushes the joystick downward and backward simultaneously, it will create side-bending left and rotation right motions to the virtual patient.

3.2 Mobile Hardware Configuration

In Figure 32, the mobile hardware configuration consists of a laptop, the Microsoft Sidewinder® Force-Feedback joystick with the vertical stand and the SensAble Omni®. The minimum system requirement for mobile configuration is listed in Table 2.

Table 2: The minimum system requirement for mobile hardware configuration

<table>
<thead>
<tr>
<th><strong>Laptop Computer</strong></th>
<th>Processor: Intel® i3 cpu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Graphic Card: NVIDIA® with 512 MB DDR3 RAM</td>
</tr>
<tr>
<td></td>
<td>System Memory: 2 GB RAM</td>
</tr>
<tr>
<td></td>
<td>Hard Drive: 120 GB</td>
</tr>
<tr>
<td></td>
<td>Operation System: Windows® XP 32 bit</td>
</tr>
<tr>
<td><strong>Force Feedback Joystick</strong></td>
<td>Direct X® compatible force feedback joystick</td>
</tr>
<tr>
<td><strong>Haptic Device</strong></td>
<td>SensAble Omni®</td>
</tr>
</tbody>
</table>
The as-sold pen stylus of the SensAble Omni® (Figure 22) was replaced by a custom-made finger holder (Figure 33) for better tactile feedback.
The VHHUB mobile hardware configuration has the full functional features of the VHHUB software and the advantages of easy transportation. It is also significantly less expensive than the laboratory hardware configuration. However, the SensAble Omni® has less force feedback and less haptic resolution than the SensAble PHANToM 3.0®.

3.3 Laboratory Hardware Configuration

The VHHUB laboratory hardware configuration is shown in Figure 34. The VHHUB laboratory hardware configuration includes a desktop computer, the Microsoft Sidewinder® Force-Feedback joystick with the vertical stand and the SensAble PHANToM 3.0®. The minimum system requirement for laboratory configuration is listed in Table 3. The current VHHUB laboratory hardware configuration only needs one SensAble PHANToM 3.0® haptic device to feel the tactile feedback. The advantages of the laboratory hardware configuration compared to the mobile unit are:

1. The SensAble PHANToM 3.0® haptic device can generate more force feedback and has higher haptic resolution than the SensAble Omni®.

2. A life size of the 3D human upper back virtual model is enabled.

<table>
<thead>
<tr>
<th>Desktop Computer</th>
<th>Processor: Intel® i3 cpu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Graphic Card: NVIDIA® with 512 MB DDR3 RAM</td>
</tr>
<tr>
<td></td>
<td>System Memory: 2 GB RAM</td>
</tr>
<tr>
<td></td>
<td>Hard Drive: 120 GB</td>
</tr>
<tr>
<td></td>
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<td>Force Feedback Joystick</td>
<td>Direct X® compatible force feedback joystick</td>
</tr>
<tr>
<td>Haptic Device</td>
<td>SensAble PHANToM 3.0®</td>
</tr>
</tbody>
</table>
The disadvantages of the laboratory hardware configuration are that it is difficult to transport and has significantly higher cost.

In Figure 35, the operator is using his left hand to apply gross motion to the virtual human model by means of a vertically mounted Microsoft Sidewinder® Force-Feedback joystick. The operator’s right hand is holding a SensAble Omni® haptic device to palpate vertebrae in the displayed virtual human model. For the lab hardware configuration, the user’s right hand holds SensAble PHANTOM 3.0® haptic device instead of the SensAble Omni®.
There are two types of hardware configuration available for the VHHUB. They both have their pros and cons.

The software development will be presented in the next section. Besides the hardware configurations, the VHHUB software is an effective tool to present our concepts to the users. The software development section is divided into mathematical calculation, 3D graphics/3D deformation editor, haptics, voice recognition/voice feedback, and gross motion palpation implementation sub-sections.
4. Software Development

The software development for the VHHUB consists of mathematical calculation, 3D graphics/3D deformation editor, haptics and speech recognition/voice feedback. Microsoft© Visual C++ is the programming language for the simulation software. The VHHUB simulation software is Microsoft© Windows compatible. The flow chart of the simulation program is given in Appendix C.

4.1 Mathematical Calculation

Calculating the forward pose kinematics solution and solving the inverse pose kinematics problem of the VHHUB (Section 2) are the essential parts of the simulation. There are two types of gross motion end-effector input, form clinical situations:

1. Active Motion: Voice commands (Section 4.4) from the user ask the virtual patient to move.
2. Passive Motion: Haptic joystick input enables the user to move the virtual patient.

The gross motion input data is used to solve the inverse pose kinematics problem in order to calculate all the joint angles during each simulation step. The next step is to calculate the pose forward kinematics solution and deformable skin using the calculated joint angles from the inverse pose solution. The 3D graphics and haptic feedback are also updated using the calculated data at each update cycle.

4.2 3D graphic/3D deformation editor

The 3D graphics of the VHHUB is generated by using the OpenGL© graphic library. The VHUUB simulation software allows the user to manipulate the 3D virtual patient (Figure 36) by zooming in/out, rotating, and/or tilting. Another unique feature of
the VHUBB software is the deformable skin editor. Figure 37 shows a screen capture of the deformable skin editor.

Figure 36: An example of 3D graphics

The deformable skin editor is a tool for the programmer who can edit the skin mesh of the 3D human model by selecting/deselecting individual or groups of skin vertices (the red dots shown in Figure 37 then adjust the weighted average of the selected skin vertices and determine which joint(s) to attach to, see Figure 38. The weighted average data of skin vertices can be saved to a data file which can be loaded when the program starts.
Figure 37: Deformable Skin editor

Figure 38: Adjustable skin vertices weighted average

Figure 39 is the screen capture of the program settings that includes user definable joint limits, points of interest (one or two) selection and enabling or disabling path following. The user can select point(s) of interests along the spine, shoulder and two arms.
In Figure 40, two drop-down lists are shown in the program settings by which the user can choose any point of interest.

**Figure 39:** A screen capture of the program settings

**Figure 40:** Choose point(s) of interest
The default human joint limits (Figure 41) are gathered from White and Panjabi (1990).

![Figure 41: Rotary joint limit ranges for the spine (White and Panjabi, 1990)](image)

### 4.3 Haptics

The Haptic (force-feedback) effects are programmed into the Virtual Haptic Human Upper Body (VHHUB) by using Direct X® and OpenHaptics® SDKs. The Microsoft Direct X® SDK is used to program the force feedback joystick. The programmer can use Direct X® build in functions to adjust the force output to the joystick and read the input joystick data. The joystick input data includes the joystick motion and which button is pressed. Any Microsoft Direct X® compatible force feedback joystick can be used by the VHHUB. However, the force output is varied from manufacturer to manufacturer. Therefore, the programmer has to adjust the force output from the joystick if needed.
The VHHUB uses the OpenHaptics® SDK to communicate with the SensAble Omni® or PHANToM 3.0®. The VHHUB can read the haptic device input data or send force commands to the haptic device. The programmer can adjust the haptic output parameters by using the OpenHaptics® SDK. These parameters are stiffness, static friction, dynamic friction and damping effects. The programmer can adjust any of these parameters to simulate different haptic effects. The VHHUB can auto detect which haptic device is connected to the computer (SensAble Omni® or PHANToM 3.0®) and adjust the proper workspace for the connected device. The PHANToM 3.0® has a much larger workspace than the SensAble Omni®.

4.4 Voice Recognition and Voice Feedback

In the VHHUB program, in addition to keyboard and haptic interface interaction, voice recognition and voice feedback technologies are implemented using the Microsoft® Speech. 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 to the virtual patient (e.g. side bending left/right, rotation left/right, and flexion/extension) which activates the VHHUB model to perform gross motions without the haptic joystick input. This feature is intended to mimic when a physician asks the patient to move by themselves (referred to as active control in Subsection 4.1). The main advantage of voice commands over the haptic joystick input is that voice input allows more degrees of freedom. The haptic joystick only permits two degree of freedom of input to the end-effector. In contrast, a voice command can give six degrees of freedom of input to the end-effector. Voice recognition technology looks for
specific key words or complete sentences depending on the programming. For example, if the user says “Please side bend to the left” or “Side bend left” then the virtual patient will side bend to the left. “Side bend” and “left” are the key words.

Another important feature is availability of voice feedback from our virtual model. Voice feedback can be used to provide additional hints (in addition to haptics) for the user to locate a specific somatic dysfunction. 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 target zones in the virtual patient. In the VHHUB program, voice feedback is also used to give correct answers to the user when he or she checks their answers during training. 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 this voice recognition technology in the Microsoft Windows® environment, users must train the computer to recognize their voice.

For multiple users using a single computer, multiple user’s voice recognition profiles can be created and transferred from one computer to another as needed. Users can create their speech recognition profile on their own computer. Users then can use the Microsoft Speech Profile Manager® (a free program) to export their speech profile to a file (Figure 42). On the VHHUB computer, the administrator can use Microsoft Speech Profile Manager® to import multiple profiles to the VHHUB computer.
When a user would like to use his or her speech profile on the VHHUB computer, he or she has to select their speech profile from the speech properties under Windows® control panel (Figure 43). This procedure is very useful for multiple users using the same computer and using only one user account similar to the current VHB training implementation.
4.5 Gross Motion Palpation Implementations

Fryette’s principles (DiGiovanna 2005; Nelson and Glonek 2006) were named after Dr. Harrison H. Fryette (1876-1960) who was a D.O.; he studies the spinal motion for many years before he published a research paper on principle of spinal motion for the American Osteopathic Association in 1918. His research work established the Physiology Principles of Vertebral Motion which is still used as a model of spinal motion today.

Fryette’s principles were implemented into our VHHUB model. There are two types of somatic dysfunction (Principle 1 and Principle 2):
1. Neutral Position- e.g. Neutral -> Side-bending (right) -> Rotation (left)

2. Non-Neutral Position- e.g. Flexion->Rotation (right) -> Side-bending (right).

Figure 44 shows side bending left for the virtual patient. Side-bending rotations are performed in the frontal plane. A rotation to the right for the virtual patient is shown in Figure 45. A rotation motion is to rotate the whole upper body to the left or right, in the horizontal plane.

*Figure 44: Side Bending Left*
For a neutral position somatic dysfunction, the feel of the transverse process of abnormal vertebrae in response to side-bending and rotation (increase/decrease resistance) are in opposite directions. For a non-neutral position somatic dysfunction, the feel of the transverse process of abnormal vertebrae in response to side-bending and rotation (increase/decrease resistance) are in the same direction. The trainee moves the virtual patient directly by using a flight-stick-type haptic interface. Then the second haptic interface will be used to perform the palpatory diagnosis on the back of the virtual patient (Figure 35).

As shown in Figure 46, a dialog box for dysfunction modifications will provide a useful tool for OMM physicians or OMM fellows to adjust the virtual human upper body’s haptic feedback during run time without a programmer’s intervention. All such adjustments can be saved to a data file. The data file will be loaded for the trainees to feel what the experts suggested the human back feels like.
With the help from the OMM fellows, the haptic feedback of somatic dysfunctions and tissue compliance of the gross motion palpation was established. We would like to ensure the realistic haptic feedback and a physiological-correct user movable human upper body. A group of experts and medical students evaluated the VHHUB. The training validation procedure and evaluation results will be presented in the next section.
5. Training Validation

Realism is crucial to the VHHUB project and our research philosophy. Osteopathic physicians and medical students are participating in two ways: 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 virtual patient.

5.1 Training Validation System

A training validation system was implemented. Every user’s training data is saved to the Microsoft® Access database for future analysis. In order to allow the VHHUB program to save training data to the database, the Open Database Connectivity (ODBC) protocol was used. In normal ODBC operation, the user has to configure the DSN (Data Source Name) manually (Figure 47).

![Figure 47: ODBC DSN configuration](image)
However, the VHHUB program can configure DSN automatically and dynamically (it will be removed from the ODBC DSN when the program is closed) without the user’s intervention. There are three tables in the Microsoft© Access database (Figure 48).

![Image of database interface showing theUserInfo table](image)

*Figure 48: Data tables*

The UserInfo table is used to store users’ information which includes name, username, password, email and user types (e.g. student or expert). The VHHUB has a log on system (Figure 49). This system can verify who is logging on and store their training data to the VHHUB database.
For a new user, he or she can create their own account without a programmer’s involvement (Figure 50). If a user forgets their password, the system can send the password via email.

The EVData table is used to store training data. The VHHUB program collects the following data from each difficulty level which the user passed:

1. Correct/incorrect answers.
2. Times to find dysfunctions.

3. Maximum and average palpation forces used by the user for each difficulty level.

4. How far off is the incorrect answer from the correct answer?

5. Which technique is used to find abnormalities? The two possibilities are Non-Neutral Position or Neutral Position technique from Fryette’s principles.

Those data can be analyzed later using Microsoft© Excel. The PostQ table is used to store post-test questions and comments (Figure 48).

The location of abnormalities on the virtual patient’s back is varied randomly and the difficulty level of the task can be varied by making the abnormalities more obvious or more subtle. In the training process, we sought to determine if training on our virtual human upper body would increase the ability of users to detect small differences in compliance between adjacent areas on the back by using gross motion palpation techniques. The smallest difference that can be detected by any sensory system of the human body is called the just-noticeable difference (JND). When this difference is expressed as a fractional change, it is known as the Weber fraction (Gescheider 1997). The Weber fraction is sometimes expressed as a percent. For example, a Weber fraction of 0.5 indicates that one can detect a 50% difference (Table 4).
Table 4: An Example of Compliance values and corresponding Weber fractions

<table>
<thead>
<tr>
<th>Difficulty Level</th>
<th>Compliance (mm/n)</th>
<th>Weber Fraction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.97</td>
<td>61.50794</td>
</tr>
<tr>
<td>2</td>
<td>1.12</td>
<td>55.55556</td>
</tr>
<tr>
<td>3</td>
<td>1.27</td>
<td>49.60317</td>
</tr>
<tr>
<td>4</td>
<td>1.42</td>
<td>43.65079</td>
</tr>
<tr>
<td>5</td>
<td>1.57</td>
<td>37.69841</td>
</tr>
<tr>
<td>6</td>
<td>1.72</td>
<td>31.74603</td>
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<td>7</td>
<td>1.87</td>
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<td>8</td>
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<td>2.17</td>
<td>13.88889</td>
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<tr>
<td>10</td>
<td>2.32</td>
<td>7.936508</td>
</tr>
<tr>
<td>Background</td>
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The difficulty levels from most obvious (level 1) to most subtle (level 10) are in a linear relationship to ensure smooth transition from level to level (Figure 51).

Figure 51: An example of linear relationship between difficulty levels
A mastery algorithm is also implemented. The purpose of the mastery algorithm is to verify the highest difficulty level achievable for each trainee in each training session. The highest difficulty level is the most subtle level of palpatory skill the trainee achieves.

For VHHUB training, 10 levels of skill level are implemented, with 1 being the more obvious (easy) and 10 being the most subtle (difficult), often approaching or exceeding the physiological limits of even the best and most experienced palpators. Increasing levels is associated with better performance and decreasing levels with worse performance. The mastery algorithm for the VHHUB training is summarized below. Each trainee is started at the easiest level.

The level is increased automatically by the VHHUB program when the trainee:

- gets 3 correct answers in a row at the current level; or
- gets 6 correct answers out of the last 10 responses at the current level.

The level is decreased automatically by the VHHUB program when the trainee:

- gives 4 incorrect answers in a row at the current level; or
- cannot get 6 correct answers out of the last 10 responses at current level.

The VHHUB program is terminated after 3 level reversals or an overall 15 minutes time limit, whichever comes first. A reversal is a change in level in the opposite direction, namely when a previous increase (or decrease) of the level is followed by a decrease (or increase) of the level. The last successful level within these constraints is defined to be the trainee’s achievement for that training session and is termed the Mastery Level. The administrator of the VHHUB can modify the mastery algorithm settings through a
program dialog (Figure 52). All the mastery algorithm settings are saved in a file and can be loaded when the program starts.

![Training Settings]

**Figure 52: Mastery algorithm Settings**

At first, we obtained the experts’ feedback and fine tuned the program. The experts are osteopathic Physicians/professors and OMM fellows at Ohio University. We also asked second-year osteopathic medical students to serve as evaluation subjects. The experts believe the VHUB will be a very useful tool to help medical students to familiarize themselves with Fryette’s principles. The medical students who evaluated the
VHUBB feel that they have more control in the VHHUB than the VHB. The user can choose any sequence of gross motion palpatory techniques as they wish. For example, they can do side bending first or rotation first. They felt more fun and more challenge when using the VHHUB compared to the VHB.

5.2 Users’ Suggestions

There are several suggestions from the experts to improve the VHHUB realism and functionality. These suggestions were added to our program to create a more realistic and user friendly medical simulator. Here are the additions to the VHHUB program from the experts:

1. **Realistic mode and Training mode for how the dysfunction reacts to gross motion:**

   This is the suggestion from two Osteopathic physicians/professors to enhance the realism of the VHHUB. In clinical practice, Osteopathic physicians use just a small amount of gross motion to detect the abnormality of a vertebra and they only keep the motion for a short time. In realistic mode the VHUBB gives the maximum dysfunction’s haptic feedback when there is gross motion (side bending, rotation or flexion/extension). The haptic feedback of the dysfunction will decrease when the user increases the range of motion.

   The training mode is the opposite. The training mode is for the user who cannot control gross motion as precisely as the experts do. By increasing the range of motion, the dysfunction’s haptic feedback from the VHHUB will increase. The
training mode will help the first time user to feel the haptic feedback of the dysfunction much easier. Either mode can be enabled by the administrator.

2. **Trainee’s Aid.**

   a. **Dysfunction location hint (Figure 53).** OMM fellows suggested giving the location hint to the trainee. In Figure 53, the yellow rectangle is the region where the dysfunction is located and the text T6 is which transverse process the trainee touched. The red sphere indicates the user’s fingertip in Figure 53.

   ![Figure 53: Location Hint](image)

   b. **3D button navigation aid (Figure 54).** This feature helps the first time user to navigate to the 3D buttons in the virtual environment. The 3D buttons are used to start the training session, pause the training and to answer questions during training. The VHHUB used 3D buttons to replace the foot switch (used in the VHB to answer training questions). The VHHUB program can run in both mobile setups and laboratory setups without the foot switch. During the training session, a trainee can use the haptic device (OMNI or PHANTOM 3)
to do all the necessary tasks without using a mouse. When the haptic pointer
is close to the proximity of a 3D button there will be a red line pointing to the
3D button from the haptic pointer (Figure 54 a). When the haptic pointer is
within proximity of a 3D button, the line will turn green and the intersect
point with the 3D button will be the location the haptic pointer towards
(Figure 54 b).

![Figure 54: 3D Button Navigation Aid](image)

All user’ aids can be turn off by the VHHUB administrator when the trainees are
comfortable regarding use of the VHHUB.

The suggestions from the experts and second year medical students are invaluable
for our research. Those suggestions make the VHHUB better for the intended customers
and will help the VHHUB become a useful learning tool for osteopathic medical students.
5.3 **VHHUB Training Procedures**

After validation by two osteopathic physicians/professors, three OMM fellows and three second year medical students, a training procedure for the VHHUB was established according to their suggestions and comments.

A trainee will be asked to create their personal account when they first use the VHHUB. This procedure will help the VHHUB to track their training data. The first VHHUB screen which the trainee will see is shown in Figure 55. We will give the trainee the opportunity to familiarize with the program. The transparency of the virtual patient is also turned on for the trainee. They can try to use gross motion palpatory techniques to feel the red rectangles (transverse processes of abnormal vertebrae). They can also change the Fryette’s Principle settings (Figure 56) to feel the different types of abnormalities before the 15 minutes training session begins. There is no time limit for the trainee to test-drive the program.
After the test drive, the trainee can use the haptic pointer to touch the ‘Start’ button to begin the training session (Figure 55). After the ‘Start’ button has been touched, the transparency of the virtual patient will be turned off (Figure 57). The upper left side of the screen shows how much time is left for the training session. On the upper right side
of the screen is the motor temperature of the haptic device (OMNI or PHANToM 3.0). This is a safety feature to protect the haptic device. When the temperature reaches the red zone, there will be a voice warning the user to use less force when palpating the virtual patient. The osteopathic physicians say this is a good feature for real-world clinical training as well. On the lower right side of the screen, there are two buttons; the ‘Pause’ button is to pause the training session and the timer. When the trainee is prepared to answer, he or she touches the ‘Check Answer’ button to verify their answer. The last transverse process the trainee touched will be the trainee’s answer to the location of the dysfunction (Figure 57).

Figure 57: A screen capture of the training session
In Figure 58, the screen capture shows what happened next when the trainee touches the ‘Check Answer’ button. The trainee has to answer the dysfunction type question by touching the ‘Neutral’ or ‘Non-Neutral’ button.

*Figure 58 Question for the dysfunction types (neutral/non-neutral)*

The second question will pop up after the trainee answers the neutral/non-neutral question. The second question is whether the dysfunction’s haptic feedback is ease to the left or ease to the right in response to side bending (Figure 59).
The trainee must get those three questions (location, dysfunction type and direction of ease) correct to pass the current trial. If the trainee gets all three correct answers, the training session will continue to the next trial. If the trainee gets one or more incorrect answers, the timer will be paused and the transparency of the virtual patient will be turned on to show the correct location, the correct dysfunction type and direction of ease (Figure 60). In the case of incorrect response(s), trainees can feel the correct answer as long as they want. After the trainee evaluates the correct answers, the trainee can touch the ‘Resume’ button to continue the training session. The processes will repeat until the 15 minutes training time ends or one of the termination conditions of the mastery algorithm is met. The difficulty level is changing automatically during the training session by following the conditions for advancing a level or reversing a level in the mastery algorithm.
Figure 60: In case of an incorrect response, the user can feel the correct answer

After the training session ends, the post-test questions will appear (Figure 61). The trainee can give their feedback or click on ‘View your training stats’ to view their training statistics for the current training session (Figure 62).
Post-test questions

1. Do you think this practice with the virtual moveable human upper body will be of help to osteopathic students learning palpation diagnosis in OMM lab?
   - No
   - Maybe
   - Yes

2. When during OMM training could this practice be most helpful?
   - During the first quarter of OMM
   - During the first year of OMM
   - During the second year of OMM
   - Anytime

3. Realism. How well do you think that the simulation of the moveable back reflects the feel of a real back? (Check one)
   - 1 2 3 4 5 6 7 8 9 10
   - Unrealistic
   - Realistic

4. Please add any comments that might be helpful in the improvement of this simulator: 1024 Characters

Figure 61: Post-test questions
Figure 62: Example of trainee training stats

Figure 62 is the screen capture of a Microsoft Excel document; it shows the training data (correct/incorrect answers, maximum/average force used on the haptic device and average time for each trial) from the first level (the easiest level) to the trainee’s mastery level.

This subsection has described the current training procedures for the VHHUB. However, these procedures can readily be modified by the administrator. In Figure 52, the administrator can adjust the total training time, how many difficulty levels and the
settings of the mastery algorithm. This will be a useful tool for setting up different training session in the future.

5.4 VHHUB Training Evaluation Results

According to the osteopathic physicians/professors’ suggestion, we only collected the evaluation data from osteopathic medical students (OMM fellows and second year medical students). Medical students’ evaluations are important because they will be the main users of the VHHUB. The main goal of the VHHUB is to help the osteopathic medical students to learn gross motion palpation techniques.

Volunteer subjects (N=5) were two OMM fellows and three second year osteopathic medical students. All volunteer subjects had previous experience of the VHB training. The laboratory hardware configuration was used (Figure 34). At the beginning of the evaluation session, all volunteer subjects were given a brief development history of the VHHUB and had the opportunity to familiarize the haptic joystick (gross motion input) and SensAble PHANToM 3.0® haptic device. They did the test drive session first. Then they began the 15 minutes training session after they were satisfied the test drive session. After the 15 minutes training session was ended, they filled out the post-test questions. All the evaluation data were collected from the 15 minute training session.

The results of the post-test questions answered by the medical students are as follow:

1. Do you think this practice with the virtual moveable human upper body will be of help to osteopathic students learning palpatory diagnosis in OMM laboratory (Figure 63)?
Figure 63: Evaluation data of the post – test question #1

2. When during OMM training could this practice be most helpful (Figure 64):
3. Realism. How well do you think that the simulation of the moveable back reflects the feel of a real back (Figure 65)?
From the preliminary evaluation data, most medical students gave a good grade on the realism of the VHHUB (Figure 65). They also felt the simulation gave them a useful tool for learning Fryette’s principles (Figure 63). From the results of the second question, half of the medical students think the VHHB will be most helpful in the first quarter or first year of the OMM class (Figure 64). Due to the reconfigurable feature of the VHHUB, osteopathic physicians/professors who evaluated the VHHUB think the VHHUB training will be very helpful at anytime of the OMM training.

The following section is the summary of the training data from the medical students who evaluated the VHHUB:

1. Trainees’ Mastery Level (Figure 66):
The result of the mastery level form 5 volunteer subjects shows only one subject reached difficulty level 5. However, this is the first time that all volunteer subjects use the VHHUB. If they can use the VHHUB program for multiple times, their mastery level should improve.

2. Maximum/average forces used by the medical students (Figure 67):
In Figure 67, the average maximum forces do not show any significant trend. However, the average force in each difficulty level indicates that the volunteer subjects tend to use more palpation force when the difficulty level increased.

3. Average time used per-trial for each difficulty level by the medical students

(Figure 68):
The result of average time used per-trial shows that in first two difficulty level the subjects try to familiarize the VHHUB program although the difficulty level is easy but they used more time for each trial. After difficulty level 2, the average time used per-trial increased when the difficulty level increased.

From the evaluation data, the VHHUB had a good response from the medical students. The VHHUB will be a helpful tool for helping the osteopathic medical students in their OMM laboratory practice.
5.4.1 Discussion

From the preliminary evaluation data the VHHUB had a good response from the osteopathic medical students. In order to validate the VHHUB for training the osteopathic medical students’ palpatory skill using gross motion palpatory diagnostic techniques, a better evaluation procedure has to be established. The goal of the VHHUB research is to improve the performance of osteopathic medical students’ clinical palpatory skill using gross motion palpatory diagnostic techniques. However, there is no objective method to measure the clinical palpatory performance. A possible approach is that the palpatory skill can be transfer between clinical palpatory training and the VHHUB training. A performance comparison between medical students and control subjects who without any OMM training. The hypothesis is that the medical students will have better performance than the control subjects on the VHHUB training.

Two groups of subject will be selected. The first group is the osteopathic medical students. The second group is the subjects who without any OMM training. All subjects will use the VHHUB laboratory hardware configuration for the evaluation. The VHHUB training procedures (Section 5.3) will be followed. It is necessary that a sequence of the VHHUB training sessions need to be performed during a period of time i.e. Subjects take the VHHUB training session 5 times each quarter for a period of one year. The sequence of training during a period of time will help us to study the transference of palpatory diagnosis skill between OMM class and the VHHUB training. The proposed validation procedure is summarized in Table 5.
Table 5: Validation procedure

<table>
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<tr>
<th>Hardware and Software</th>
<th>VHHUB Laboratory Hardware and VHHUB software</th>
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<tr>
<td>Experiment subjects</td>
<td>1. Osteopathic medical students</td>
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<tr>
<td></td>
<td>2. Control group: Subjects without any OMM training experience</td>
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<tr>
<td>Testing procedure</td>
<td>The VHHUB training procedure</td>
</tr>
<tr>
<td>Experiment period</td>
<td>Multiple VHHUB training sessions (i.e. 5 times per quarter for a year)</td>
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The conclusion of the VHHUB research project and future research work recommendations will be presented in the next section.
6. Conclusions and Future Work

6.1 Summary and Conclusions

The Virtual Haptic Human Upper Body (VHHUB) is a major addition to our Virtual Haptic Back (VHB) product since it represents the first time the 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. The virtual human upper body is a 71 degrees-of-freedom multiple end-effectors, multi-branching serial chain model. It has fully movable thoracic and lumbar spinal regions plus two shoulders and two arms with a deformable body (Chen et al. 2006). By comparison, other virtual human research has much less detailed spinal structure. The goal of the VHHUB research is to create a physiologically-correct human upper body for gross motion palpation training using haptics and virtual reality technologies (Chen et al. 2009b).

Due to the complexity of the VHHUB model, we presented a velocity inverse kinematic problem solver with dynamic pivot point. This method ensures a smooth synchronization rate between graphics and haptic hardware in real time. A smooth synchronization rate between graphics and haptic hardware is crucial in haptic simulation. If there is a time delay, the user will not have a realistic feedback from the graphics or haptics.

In order to simulate real clinical practice, two gross motion input methods are developed (Chen et al. 2009a). A haptic joystick is used as the virtual patient passive motion input for gross motion. Voice commands are used as the active motion input to the virtual patient. Speech recognition capability is not only for using voice commands but also the voice feedback from the virtual patient. A user can give voice commands to
induce gross motion to the virtual patient. He or she can also ask questions of the virtual patient and receive virtual patient voice feedback.

One of the important features of the VHHUB is the implementation of Fryette’s principles. Dr. Fryette established the Physiology Principles of Vertebral Motion which is taught in OMM training classes today. The VHHUB helps the osteopathic medical students to learn Fryette’s principles. With help from osteopathic physicians and osteopathic medical students we established a training procedure. The VHHUB training procedure can test medical students’ understanding of gross motion palpation techniques. It also helps students to learn from their mistakes.

The VHHUB software is developed in a way to help osteopathic physicians or OMM fellows to fine tune the program. The haptic feedback of somatic dysfunctions can be modified by OMM faculty administrators without any knowledge of a programming language. Other adjustable program parameters are training time, mastery algorithm characteristics and human joint limits. All adjustable parameters can be saved and used repeatedly. The administrators can adjust the VHHUB program to fine-tune the realism of the haptic feedback and modify the training procedure to enhance the learning experience.

From the preliminary evaluation data, most medical students gave 7 or up (scale from 1 to 10: 1 is unrealistic and 10 is realistic) on the realism of the VHHUB (Figure 65). Medical students also felt the simulation gave them a useful tool for learning Fryette’s principles (Figure 63). Half of the medical students who evaluated the VHHUB think the VHHB will be most helpful in the first quarter or first year of the OMM class (Figure 64).
Because of the reconfigurable feature of the VHHUB, osteopathic physicians/professors who evaluated the VHHUB think the VHHUB training will be very helpful at anytime of the OMM training.

The VHHUB is a reconfigurable and repeatable virtual medical simulator for the osteopathic medical training. From the preliminary evaluation results by the experts and the second year osteopathic medical students, the VHHUB will serve well to augment the teaching and learning tool of gross motion palpatory diagnosis techniques in the OMM training classes.

6.2 Recommendations for Future Work

There are several possible suggestions for future work in this area.

1. The VHHUB generates simple gross motions (side bending, rotation and flexion/extension) for gross motion palpation training. More complex motions can be adapted using our virtual patient model. An advanced end-effector path planning can be a good research topic and can be used in other medical training objectives.

2. The VHHUB is used for palpatory diagnoses training. It is possible to expand the VHHUB to simulate the manipulative treatment of patients with spinal dysfunctions. A limitation is the haptic device currently cannot generate enough force to simulate the force induced by the osteopathic physicians during certain clinical treatments of some patients.

3. The body of the VHHUB virtual patient deforms when the underlying skeletal system moves. However, the skin surface of our virtual patient will not deform
when the user’s virtual fingertip touches. By combining the skin surface deformation methodology (Ji 2008), the realism of the virtual patient will increase to a great extent. The additional cost of mathematical computation will be the main consideration.

4. The thoracic and lumbar spinal regions are modeled in the VHHUB virtual patient. Our inverse kinematics problem solver with dynamic pivot point can be modified to accommodate additional branches of the spinal column. For example the cervical spine can be added to our virtual patient to create a more complete human upper body model.

5. Development of different tasks should be programmed to assist in OMM training by using the VHHUB virtual patient model as a foundation.
References


Appendix A: List of D-H Parameters

The complete list of D-H parameters of the 71 degree-of-freedom virtual human upper body model is shown in the following table.

**D-H parameters:**

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</tr>
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</tr>
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</tr>
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</tr>
<tr>
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<td>( \theta_{52} )</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
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<tr>
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<td>$\theta_{62}$</td>
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<td>0.0</td>
<td>$\pi/2 + \theta_{65}$</td>
</tr>
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<td>0.0</td>
<td>$\pi/2 + \theta_{66}$</td>
</tr>
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<td>0.0</td>
<td>0.0</td>
<td>$\pi/2 + \theta_{67}$</td>
</tr>
<tr>
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<td>$\pi/2$</td>
<td>Rd3</td>
<td>0.0</td>
<td>$\pi/2 + \theta_{68}$</td>
</tr>
<tr>
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<td>0.0</td>
<td>$\pi/2 + \theta_{69}$</td>
</tr>
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<td>$\pi/2$</td>
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<td>0.0</td>
<td>$\pi/2 + \theta_{70}$</td>
</tr>
<tr>
<td>71</td>
<td>0.0</td>
<td>Rd4</td>
<td>0.0</td>
<td>$\theta_{71}$</td>
</tr>
</tbody>
</table>

**List of parameters:**

L1: Vertebra height of L1.
L2: Vertebra height of L2.
L3: Vertebra height of L3.
L4: Vertebra height of L4.
L5: Vertebra height of L5.

T1: Vertebra height of T1.
T2: Vertebra height of T2.
T3: Vertebra height of T3.
T4: Vertebra height of T4.
T5: Vertebra height of T5.
T6: Vertebra height of T6.
T7: Vertebra height of T7.
T8: Vertebra height of T8.
T10: Vertebra height of T10.
T11: Vertebra height of T11.
T12: Vertebra height of T12.

Ld1: Left clavicle offset.
Ld2: Left clavicle length.
Ld3: Left scapular length.
Ld4: Left upper arm length.

Rd1: Right clavicle offset.
Rd2: Right clavicle length.
Rd3: Right scapular length.
Rd4: Right upper arm length.
Appendix B: Derivation of $J_v$ and $J_\omega$

The detailed derivation of the upper half and lower half of Jacobian matrix $J = \begin{bmatrix} J_v \\ J_\omega \end{bmatrix}$ (Spong and Vidyasagar 1989) is as follows:

1. $J_v$

   The linear velocity of the end-effector is $\dot{d}_n^0$. Follow the chain rule for differentiation we have:

   $$\dot{\dot{d}}_n^0 = \sum_{i=1}^{n} \frac{\partial \dot{d}_n^0}{\partial q_i} \dot{q}_i$$  \hfill (28)

   Thus the $i$-th column of $J_v$ is $\frac{\partial \dot{d}_n^0}{\partial q_i}$. However this expression is just the linear velocity of the end-effector that would result if $\dot{q}_i$ is equal to one and the other $\dot{q}_j$ are zero. In other words, the $i$-th column of the Jacobian is derived by fixing all joints but the $i$-th and actuating the $i$-th joint at unit velocity. We have to consider two cases separately.

   (a) Case 1

   If the $i$-th joint is prismatic, then $R_i^j$ is independent of $q_i = d_i$ for all $j$ and

   $$d_i^{l-1} = d_iK + \sum_{i=1}^{l-1} R_i^j d_j^0 \quad \hfill (29)$$

   where $K = (0,0,1)^T$ and $i = (1,0,0)^T$.

   If all joints are fixed but the $i$-th joint we can have

   $$\dot{\dot{d}}_n^0 = 0 \dot{R}_i \dot{d}_i^0$$

   $$= \dot{d}_i^0 0 \dot{R}_i K$$

   $$= \dot{d}_i^0 z_i \quad \hfill (30)$$
Thus

\[ \frac{\partial d_0^i}{\partial q_i} = Z_i \]  \hspace{1cm} (31)

(b) **Case 2**

If the \( i \)-th joint is revolute, let \( d_i^0 \) is from the origin \( o_0 \) of the base frame to the origin \( o_i \) of any joint frame, we have

\[
d_0^i = d_i^0 + {}^0_i R \, d_n^i \]  \hspace{1cm} (32)

or

\[
o_n - o_i = {}^0_i R \, d_n^i \]  \hspace{1cm} (33)

\[\text{Figure 69: Motion of the end-effector as a result of link } i.\]

From Figure 69, both \( d_i^0 \) and \( {}^0_i R \) are constant if only the \( i \)-th joint is actuated.

Therefore
The motion of the \( i \)-th link is a rotation \( q_i \) about \( z_i \) we have

\[
\dot{d}_n^i = q_i K \times d_n^i
\]  
(35)

and we have

\[
\dot{d}_n^0 = (q_i K \times d_n^i)
\]

\[
= \dot{q}_i (0 \times d_n^i)
\]

\[
= \dot{q}_i z_i \times (o_n - o_i)
\]  
(36)

Thus

\[
\frac{\partial d_n^0}{\partial q_i} = z_i \times (o_n - o_i)
\]  
(37)

and \( J_v \) is given as

\[
J_v = [J_{v1} \ldots J_{vn}]
\]

If the \( i \)-th joint is revolute, the \( i \)-th column \( J_{vi} \) is

\[
J_{vi} = z_i \times (o_n - o_i)
\]  
(38)

If the \( i \)-th joint is prismatic, the \( i \)-th column \( J_{vi} \) is

\[
J_{vi} = z_i
\]  
(39)

2. \( J_\omega \)

The angular velocity of the \( i \)-th link expressed in the joint frame \( i-1 \) is

\[
\omega_i^{i-1} = (i-1)^{-1} R \dot{q}_i K
\]  
(40)

If the \( i \)-th joint is prismatic, then the motion of frame \( i \) relative to frame \( i-1 \) is a translation and
Therefore, if the i-th link is prismatic the angular velocity of the end-effector does not depend on $q_i$, which is now equals to $d_i$.

Thus the overall angular velocity of the end-effector $\omega^n_0$ is

$$\omega^n_0 = \rho_1 \dot{q}_1 K + \rho_2 \dot{q}_2^0 R K \cdots + \rho_n \dot{q}_n^0 R K$$

$$= \sum^0_i \rho_i \dot{q}_i z_i \qquad (42)$$

where

$$z_i = ^0_i R K$$

$$z_0 = K = (0,0,1)^T$$

$J_\omega$ is given by

$$J_\omega = [\rho_1 z_0 \ldots \rho_n z_n]$$

where $\rho_i$ is equal to 1 if joint i is revolute and $\rho_i$ is equal to 0 if joint i is prismatic (with no rotation).
Appendix C: The VHHUB Program Flow Chart

Active Motion
Voice Command

Passive Motion
Joystick Input

\( dE, \) [6x1]
Changes of end effector

Inverse Kinematics find \( \theta, \) and \( \theta_{i+1} = \theta_i + d\theta_i \)

\( \theta_{i+1}, \) check joint limits
If any \( \theta_{i+1} \geq \) any \( \theta_{\text{limit}} \)
else proceed to next step

\( \theta_{i+1} \)
Forward Kinematics-finds \( E_r \)

If \(|E_r - E| > \delta\) ---►
else proceed to next step

Update Deformable Skin
Update 3D graphics
Update haptics

User: Find dysfunction(s)
Save user’s data
Change dysfunction location and compliance
for next training.

Dynamic Apex

\( dE = \frac{1}{2}(dE) \)
recalculate Inverse Kinematics