A Virtual Reality Based Prototype System of Spinal Kinematics Simulation

Yueh-Chien Ho and Don-Lin Yang
Institute of Information Engineering
Feng Chia University, Taichung, Taiwan
<dlyang@fcu.edu.tw>

Chen-Hsing Peng and Chia-Hsien Wen
Computer Center, Taichung Veterans
General Hospital, Taichung, Taiwan
<chpeng@vghtc.vghtc.gov.tw>

Abstract

With the emergence of virtual environments and powerful interfaces between users and computer devices, many practical applications, especially those related to 3-D visualization, can benefit from Virtual Reality based simulation systems. Our research concerns the VR-based presentation of spinal movement and kinematics simulation. We propose a general prototype system implementation and use the concept of object hierarchy as the basis of component generation. Owing to the high complexity of real spinal movement, the biomechanical metrics in our system has been simplified to meet performance requirements with less manual involvement. Three methods, namely the decrement method, the segmented decrement method, and the force decomposition method, are presented to generate angular variations after imposing a force on an object, e.g., a vertebra of spine, in a virtual environment. The first two methods are based chiefly on hypotheses, and they become the guidance of the last method. As a result, users can freely interact with objects in terms of force exertion and observe the spinal movement at any angle in our simulation system. Moreover, our system can provide therapists with a kinematic platform to demonstrate biomechanics and rehabilitation training.

Keywords: *Virtual Reality, Biomechanics, Kinematics Simulation, Spinal Rehabilitation*

1 Introduction

Currently, the simulation of human animation has become more and more popular. Due to the nature of constantly evolving technology, many sophisticated computations and graphical processing problems can be solved gradually. This trend has led 3-D computer graphics to reach a new horizon, becoming the fundamental assessment of personal computer capability in multimedia. Other requirements placed on movies, mass communication, advertisements, games, virtual reality (VR), etc., have also contributed to the evolution of human motion simulation. In such a virtual environment, users or participants can immerse in a vivid scene and interact with all kinds of objects, e.g., human bodies. This 3-D environment presents more degrees of freedom (DOF) than pure images and reveals more sensory information and stimulus of the real world [1]. These properties make VR prevalent, especially in visualized tasks. Taking advantage of the above properties, we construct a simulation system of human spinal motion based on virtual reality technology and provide users with interaction mechanisms, i.e., force exertion on a vertebra, between participants and our spinal geometry.

Our motivation arises from the need to educate people to become aware of wrong postures of their spines. Nowadays, more and more people are suffering from spinal diseases and low back pain because of long period of sitting and inadequate designs of chairs. These problems may become more severe due to neglect, and they pose as threats to our health, physiological conditions, and even psychological aspects. However, it requires a long time for spinal rehabilitation to take effect. Our VR-based kinematic simulation system provides interactive demonstration and benefits spine-injured persons for motor pattern learning. Moreover, senior therapists can use it as an educational tool to tutor younger therapists. Ultimately, our objective is to provide a flexible platform of kinematic simulation capable of easily adapting to other human joints, or even robot arms.

2 Related Work

Since VR is especially suitable for applications in visualization, a VR-based surgical simulation can reduce a lot of effort in medical training. VR is also used as a tool to cure psychological phobias, e.g., acrophobia, flying-phobia, arachnephobia, etc. [3][4]

The research methodologies on Kinesiology include the following:

1) Experimental method: Several kinds of medical instruments are used to measure the physiological signals of living creatures. By carefully analyzing the statistical results of these signals, we may draw some conclusions in a specific condition. For example, the Electromyography (EMG) method is well known in the research field.
2) Photographic method: We can tape some surface markers, reflectors, or something easily traced and identified on our body surfaces [12], then use a high-speed or an X-ray camera to estimate the spatial and temporal relation of human bodies.
3) Mathematical method: In contrast to the experimental method, this method is more theoretical. What matters here is that the mathematical or mechanical analyses only state parts of Kinesiology; we must find out the correlation between muscles and skeleton and also how they interact with each other.

Based on the concept of object hierarchy, we adopt a general human body hierarchy to form the relationship of human body components. This hierarchy is similar to a tree structure. The position of the pelvis, i.e., the root, is near the center of mass of a person in a standing pose. According to this hierarchy, the coordinate systems of child objects are relative to those of parent objects, and it is quite intuitive for position maintenance.

As for our spinal geometry, it can be anatomically classified into five categories: the Cervical Spine (C1~C7), the Thoracic Spine (T1~T12), the Lumbar Spine (L1~L5), the Sacrum (S1~S5), and the Coccyx. Among them, the vertebrae of the Sacrum and Coccyx are fused together individually, and we focus our interests on the first three segments of the spine, which are composed of twenty-four vertebrae and twenty-five joints. A complete spine is made up of these vertebrae and their neighboring joints. We call a pair of two consecutive vertebrae and the in-between soft tissue, i.e., an intervertebral disc, a Functional Spinal Unit (FSU), which is regarded as a basic motor unit. Apparently, an entity (or object) in our system is composed of one vertebra and a joint beneath the vertebra.

In addition to the composition of the spine, its resting curvature is similar to an "S". Strictly speaking, the Cervical Spine and Lumbar Spine belong to Lordosis in appearance, and contrarily, the Thoracic Spine belongs to Kyphosis. This specification reflects the spatial correlation of all vertebrae of a person in sitting posture. Due to the lack of initial angles of consecutive vertebrae, all the vertebrae of a spine are arranged with the help of experienced therapists.

To simulate more vivid spinal movement, we have to take the spatial constraints of the vertebrae into consideration, i.e., the angular constraints of flexion, extension, lateral flexion, and rotation will be specified. Normally, the Cervical Spine and Lumbar Spine provide most of the angular variations in flexion and extension, and rotation is mainly dictated by the Cervical Spine.

Extra prerequisites are often needed for problem solving. [6] Since our objectives emphasize the performance of force and motion, we clarify our question to "how much force exertion on a specific vertebra will generate what kinds of motion". An inverse manipulation known as a reverse solution will reflect other interests on force calculation. [5]

Our VR-based spinal kinematics system provides interaction for applying force on the vertebrae and requires time-consuming algorithms of collision detection. The efficiency of algorithms depends on the strategies and the geometric models of objects. Some issues may arise regarding multi-cooperative networked environment, e.g., Distributed Interactive Simulation (DIS), and a certain amount of network topology or protocols are thus tailored to fit the needs in such a virtual environment. [2]

3 Our Proposed System

Our system has two phases: the preprocessing phase and the simulation phase.

As shown in Figure 1, the left portion enclosed by dotted lines belongs to the former, and the right portion is the simulation phase, which provides an environment for kinematic trials in virtual reality. In our real-time simulation we impose a force on one vertebra of the spine, and observe its movement in our virtual world. In the following we will discuss the content of each phase.

(A) The preprocessing phase: This phase prepares for the spinal movement trials and contains spinal model construction, interactive behavior definition, and the arrangement in virtual reality.

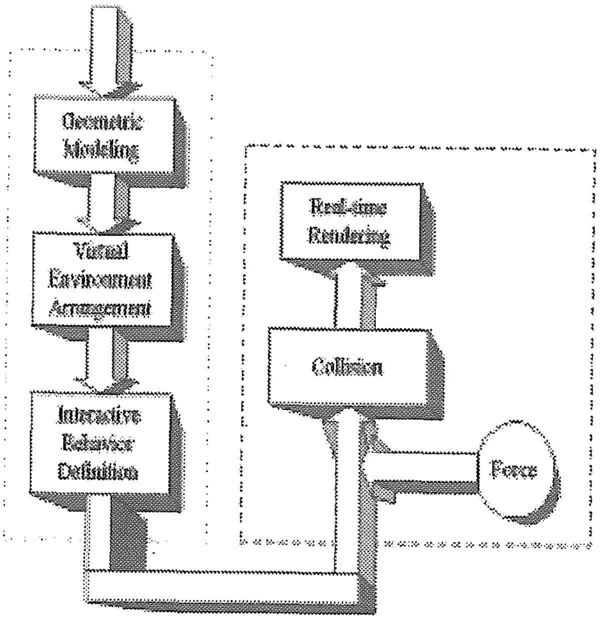


Figure 1. The flowchart of our simulation system

(A.1) Geometric modeling: We sketched the geometric surfaces of vertebrae in our system using 3D Studio Max software and three views of the vertebrae. Based on object hierarchy, we treat each vertebra as an object and link their hierarchical relationship. The spine consists of more than 200 geometric components while each component is made up of about 300 triangles. We can merge the vertices, remove the redundancy, and do some optimization of our geometric models to enhance the rendering performance. Stripping out triangles, joining surfaces, aligning surfaces, etc., are usually useful for geometric reduction. [8][9] Furthermore, one may adopt 3-D reconstruction skills to render more accurate surfaces from specific slices, e.g., CT scans. Image interpolation [10], segmentation [11], registration, etc., can be applied to this domain, but it involves many complex procedures. The manual involvement here is that therapists suggest the initial angles between consecutive vertebrae.

(A.2) Virtual environment arrangement: Regarding each vertebra or FSU joint as a basic element in the simulation, we take the whole vertebrae as a multi-segment linkage. The spatial arrangement and force interaction of the spine are shown in Figure 2.

(A.3) Interactive behavior definition: Here, an interaction is defined as how a vertebra moves after imposing a force on it, which is shown in Figure 3. Once a force exertion is applied upon a vertebra, the touched vertebra will be moved in an angle resulted from biomechanical metrics, i.e., angular computation, and it will simultaneously transmit its force impact on the neighboring vertebrae. Followed by constraint consideration, the above angle will be modified to an appropriate range, i.e., final angular variation. A similar reaction takes place in the neighborhood of the initially invoked vertebra until the force impact disappears.

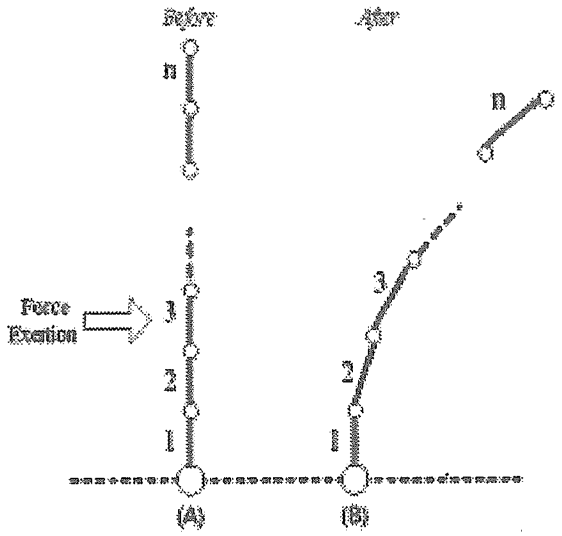


Figure 2. Spatial arrangement and force interaction of spine

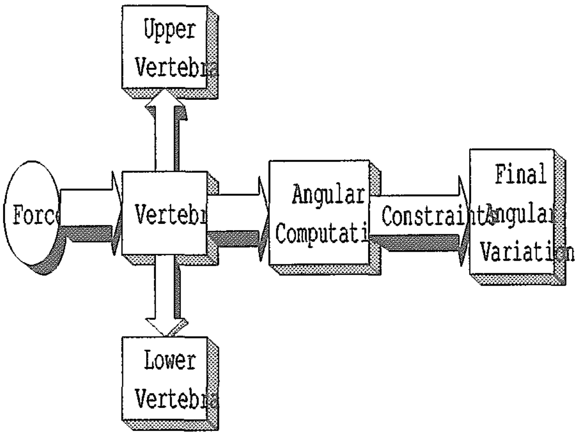


Figure 3. The diagram of interaction between the vertebrae and force

(B) The simulation phase: This phase is based on interactive behaviors defined in our system and provides us with trials on spinal movements. Users can change to any positions or viewing angles in our VR-based simulation.

With regard to the angular computation in Figure 3, we propose three kinds of biometrics, namely the Decrement Method, the Segmented Decrement Method, and the Force Decomposition Method, to compute the angular variations after the spine has been touched.

Method 1: The Decrement Method

The Decrement Method uses an *extremely simplified* paradigm. The hypothesized basics of this method are as follows: the force-exerted vertebra will generate virtual angular variations with gradually outward decrement in angles along its neighboring vertebrae and will simultaneously influence other vertebrae until this impact disappears. This situation is like a spring, say, a specific point of the spring is touched by hand, the force impact will transfer outward gradually.

For a more detailed description of the Decrement Method, an initial value $Offset$ and two decreased functions $ratioUp()$ and $ratioDown()$ are set to each vertebra. The angular variation of this force-exerted vertebra is set to the product of the external force F and the initial value $Offset$, i.e., $F \times Offset$. The force exertion on the neighboring vertebrae, i.e., $transF\_Up$ and $transF\_Down$, are function values of the external force F in two decreasing functions $ratioUp()$ and $ratioDown()$, i.e., $ratioUp(F)$ and $ratioDown(F)$ respectively. Figure 4 shows an example of angular variations with a unit of force exertion on T6.

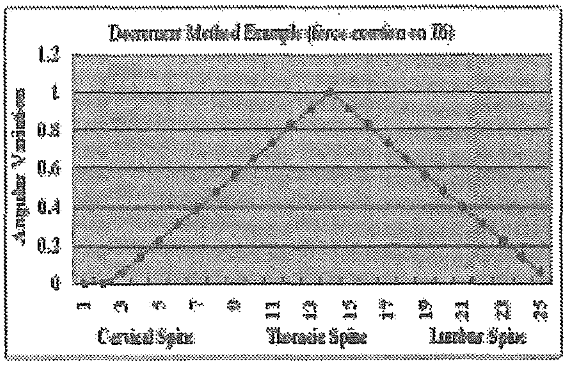


Figure 4. An example of angular variations with force exertion on T6 in the Decrement Method

Method 2: The Segmented Decrement Method

For moderately reducing the number of parameters, we can use the curvature of spine to express the characteristics of individual segmented spines. That is, the vertebrae on the Cervical Spine, the Thoracic Spine, and the Lumbar Spine have different parameters. An example of angular variations with a unit of force exertion on T6 is shown in Figure 5. With angular variations decreasing outward along T6, the slopes of angular decrement in the Cervical Spine and the Lumbar Spine are all different.

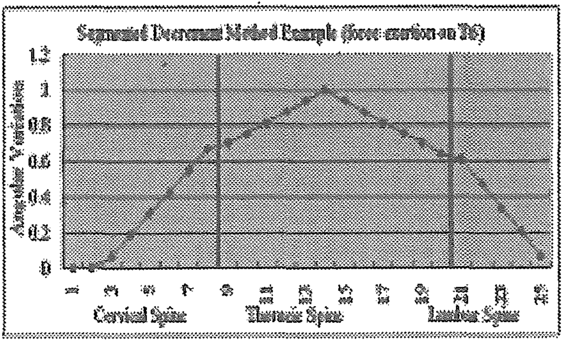


Figure 5. An example of angular variations with force exertion on T6 in the Segmented Decrement Method

Method 3: The Force Decomposition Method

The Force Decomposition Method uses rules based on Mechanical Engineering and Kinesiology to regulate the computation of angular variations. Before our discussion, we need to make some definitions.

We assume there are n rigid and even linkages; their mass, length, and torque (or moment) are m_i, l_i, and M_i respectively. The distance between the center of mass and the individual ends of linkage is r_i. Assume that we impose an external force F on the k th linkage (with l_0 distance relative to its lower end), each linkage then generates an angular variation θ_i perpendicular to the horizontal as shown in Figure 6. The indexes of linkage from the lowest position to the highest position are 1 to n, and the gravity is expressed as g. What will θ_i be?

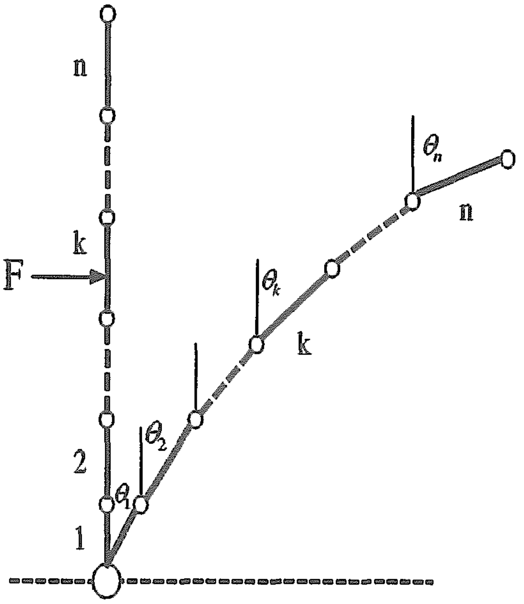


Figure 6. The setting for Force Decomposition Method

Based on the setting in Figure 6, we adopt the rationale of virtual work in Statics to solve our problem. This rationale is especially useful in solving problems with a multi-linkage system. The virtual work rationale states that when an ideal mechanical system is in the status of balance, the virtual work due to external forces is zero during the period of virtual displacement with all constraints coincided. In terms of work, a simplified version of the total energy U can be expressed as follows:

$$\begin{aligned}&U = m_1 g[r_1 - r_1\cos !_1] + m_2 g[(l_1 + r_2) - (l_1\cos !_1\\&+ r_2\cos !_2)] + m_3 g[(l_1 + l_2 + r_3) - (l_1\cos\theta_1 +\\&l_2\cos\theta_2 + r_3\cos\theta_3)] + \ldots\ldots + m_n g[(l_1 + l_2 + \ldots +\\&l_{n-1} + r_n) - (l_1\cos\theta_1 + l_2\cos\theta_2 + \ldots +\\&l_{n-1}\cos\theta_{n-1} + r_n\cos\theta_n)] + F(l_1\sin\theta_1 +\\&l_2\sin\theta_2 + \ldots + l_{k-1}\sin\theta_{k-1} + l_0\sin\theta_k) -\\&(M_1\theta_1 + M_2\theta_2 + \ldots + M_n\theta_n)\end{aligned} \quad \text{(Eq. 1)}$$

While the status of balance is achieved, the partial differential with angle θ_i to Eq. 1 is zero, i.e. $\frac{\partial U}{\partial \theta_i} = 0$.

$$\begin{aligned}&\frac{\partial U}{\partial \theta_1} = 0,\ g\sin\theta_1(m_1 r_1 + m_2 l_1 + m_3 l_1 + \ldots + m_n l_1) +\\&F l_1\cos\theta_1 - M_1 = 0\end{aligned} \quad \text{(Eq. 2)}$$

$$\begin{aligned}&\frac{\partial U}{\partial \theta_2} = 0,\ g\sin\theta_2(m_2 r_2 + m_3 l_2 + m_4 l_2 + \ldots +\\&m_n l_2) + F l_2\cos\theta_2 - M_2 = 0\end{aligned} \quad \text{(Eq. 3)}$$

……………………………………………………

$$\begin{aligned}&\frac{\partial U}{\partial \theta_{k-1}} = 0,\ g\sin\theta_{k-1}(m_{k-1} r_{k-1} + m_k l_{k-1} + \ldots +\\&m_n l_{k-1}) + F l_{k-1}\cos\theta_{k-1} - M_{k-1} = 0\end{aligned} \quad \text{(Eq. k)}$$

$$\begin{aligned}&\frac{\partial U}{\partial \theta_k} = 0,\ g\sin\theta_k(m_k r_k + m_{k+1} l_k + m_{k+2} l_k\\&+ \ldots + m_n l_k) + F l_0\cos\theta_k - M_k = 0\end{aligned} \quad \text{(Eq. k+1)}$$

$$\begin{aligned}&\frac{\partial U}{\partial \theta_{k+1}} = 0,\ g\sin\theta_{k+1}(m_{k+1} r_{k+1} + m_{k+2} l_{k+1} +\\&m_{k+3} l_{k+1} + \ldots + m_n l_{k+1}) - M_{k+1} = 0\end{aligned} \quad \text{(Eq. k+2)}$$

……………………………………………………

$$\frac{\partial U}{\partial \theta_n} = 0,\ g\sin\theta_n(m_n r_n) - M_n = 0 \quad \text{(Eq. n+1)}$$

From above, we divide equations into two categories for solutions: Eq. 2 ~ Eq. k+1 and Eq. k+2 ~ Eq. n+1. The solutions are as follows:

(1) When $i = 1,2,\ldots,k\ !\ \ \theta_1 \sim \theta_k$

$$\sin(\theta_i) = \frac{M_i A_i \pm B_i\sqrt{A_i^{\,2} + B_i^{\,2} - M_i^{\,2}}}{A_i^{\,2} + B_i^{\,2}} \quad \text{(Eq. n+2)}$$

where $A_i = g(m_i r_i + m_{i+1} l_i + m_{i+2} l_i + m_{i+3} l_i + \ldots + m_n l_i)$

$B_i = F l_i$

(2) When $i = (k+1),(k+2),\ldots,n\ !\ \ \theta_{k+1} \sim \theta_n$

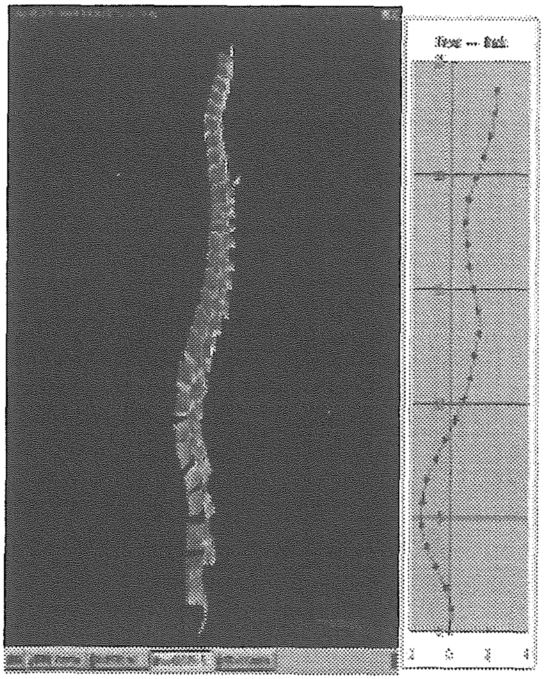
$$\sin(\theta_i) = \frac{M_i}{g(m_i r_i + m_{i+1} l_i + m_{i+2} l_i + \ldots + m_n l_i)} \quad \text{(Eq. n+3)}$$

The relations between the external force F, the moment of vertebra M_i, and the angular variation θ_i are quite obvious from Eq. n+2 and Eq. n+3, but these relations do not guarantee that these equations will be solved. The fact is that the number of our preconditions is fewer than that of actual unknowns. It is hard to formulate a generalized kinematic equation using implicitly minimal degrees of freedom. The actual DOFs are often more than what is needed for humans to perform a specific motion. The question comes to how we can remove redundant supports and achieve the statically determinate status. Under such circumstances, equations are sufficient for solving the unknowns. However, we have to find some reasonable ways for parameter simplification.

Owing to the complex nature of the spine, it is probably impossible to find physiological evidence to simplify Eq. n+2 and Eq. n+3. Our solution for the Force Decomposition Method is to rationalize the first two methods via therapists and make them become reasonable paradigms for spinal kinematics simulation. By applying reverse steps in the Decrement Method and the Segmented Decrement Method, we can acquire the torques of the vertebrae via the relation between force exertion and angular variations. Finally, the acquired torques of the vertebrae become the given parameters in Eq. n+2 and Eq. n+3.

4 Experimental Results and Evaluation

Figure 7 displays the dVISE-based [7] interface of our simulation system. The initial positions of the vertebrae and their relative angles set by therapists are shown in Figure 7 (B) and Table 1.



(A) (B)

Figure 7. (A) The dVISE interface of our simulation system. (B) The initial position of the vertebrae

The execution of the system shown in the right part of Figure 1 follows our interactive setup. We impose a force on one of the vertebrae. Then the vertebra being touched will move to its destination according to its underlying biometrics. We compare the results with different metric methods. In order to form a regulating routine for comparisons, we impose a force on the T6 vertebra several times, e.g., five times, and observe its movements in our 3-D VR environment.

Results of the Decrement Method

As shown in Figure 4, we use the same assumption that the vertebra T6 is touched with a unit of force exertion, and its neighboring vertebrae have a slightly decreasing effect outward along T6. Figure 8 shows the spatial movements of continuous force exertion on T6 in the Decrement Method. Note that the decreasing rate of the lower segment of the spine, i.e., the lumbar spine, is smaller than that of the upper segment of the spine. This is because the former bears a larger load than the latter, thus obtaining larger angular variations in movements.

Results of the Segmented Decrement Method

In the Segmented Decrement Method, we apply a different strategy of taking each of three segments of the spine as a whole to distinguish their differences.

index	Vertebrae	Constraints				Initial Angle	Angular Ranges	
		Flexion / Extension		Lateral Flexion / Rotation				
1	C0	10	15	3.5	3.2	-7	-17	8
2	C1	5.8	6.9	0	33.9	-9	-14.8	-2.1
3	C2	7.6	4.9	5	10	-3	-10.6	1.9
4	C3	8.4	9.2	5.7	10	2	-6.4	11.2
5	C4	8.9	11.1	4.2	10	13	4.1	24.1
6	C5	10	10.3	2.5	10	14	4	24.3
7	C6	10	6.2	4.2	10	1	-9	7.2
8	C7	4.2	3.3	4	8.2	9	4.8	12.3
9	T1	2.2	2.1	2.3	2.3	-2	-4.2	0.1
10	T2	2.2	2.1	2.3	2.6	-11	-13.2	-8.9
11	T3	2.2	2.1	2.3	4.2	-14	-16.2	-11.9
12	T4	2.2	2.1	2.3	4.6	-1	-3.2	1.1
13	T5	2.2	2.2	1.8	1.9	-8	-10.2	-5.8
14	T6	1.7	1.7	2.2	4.5	-2	-3.7	-0.3
15	T7	1.6	1.6	3.1	3.6	-8	-9.6	-6.4
16	T8	1.5	1.3	1.7	3.5	2	0.5	3.3
17	T9	1.1	1	3	3.5	1	-0.1	2
18	T10	2.4	2.2	3	3.5	16	13.6	18.2
19	T11	6.5	3	3.5	3.5	9	2.5	12
20	T12	7.4	3.8	3.5	3.5	18	10.6	21.8
21	L1	8.2	4.3	4.1	3.5	15	6.8	19.3
22	L2	9.7	3.9	5.3	3.5	-1	-10.7	2.9
23	L3	11.1	2.9	6.4	3.5	-12	-23.1	-9.1
24	L4	13.8	3.9	3.5	2.5	-20	-33.8	-16.1
25	L5	11	4.9	2.6	2.5	3	-8	7.9

Table 1. The initial angles of the vertebrae

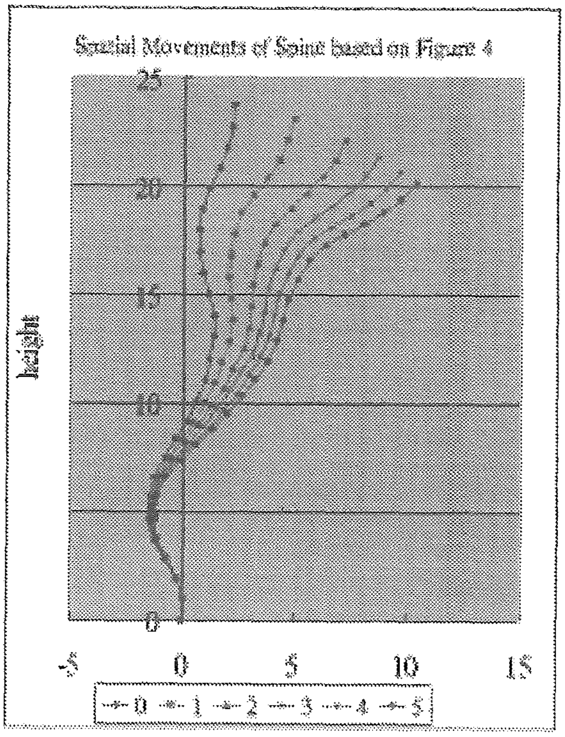


Figure 8. Continuous force exertion on T6 in the Decrement Method based on Figure 4

Figure 9 shows spatial movements of continuous force exertion on the T6 vertebra with a unit of force. In this case, we can see that each segment of the spine has different decreasing rates of angular variations. With a reduction on the computation of angular variations, we can put more emphases on individual segments of the spine instead of individual vertebrae; generally, the former is regarded with more significance than the latter.

Results of the Force Decomposition Method

Our Force Decomposition Method is based on biomechanics. As we mentioned earlier, some measurements of human body are not easily available, e.g., the mass or inertial moment of a vertebra. Based on the concept of virtual work, our solution is to rationalize the spinal movement via the first two methods to acquire the moment of each vertebra. Table 2 is a result of our parameter setting in the Force Decomposition Method. To simplify the illustration, we assume $m_i=1$, $l_i=1$, and $r_i=0.5$.

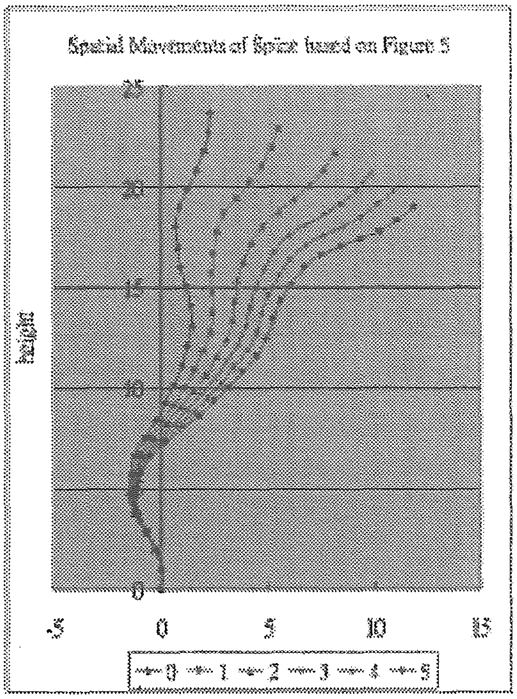


Figure 9. Continuous force exertion on T6 in the Segmented Decrement Method

In the first column of "Angular Variations" is "Virtual Angles" directly derived from angular computation by applying a unit of force on T6. Taking spatial constraints of vertebrae into consideration, the second column shows the final angles applied to the vertebrae. Graphical results on T6 are shown in Figure 10.

Evaluation

In general, we evaluate experimental results in qualitative and quantitative analyses. To serve the purpose of performing educational functions, the therapists were invited to examine our kinematics simulation system. Therefore, we use subjective rather than objective evaluations.

Verte-bra	Ini-tial	Constraints (Angles)		Parameters				Angular Variations	
		Flexion	Extension	m_i	l_i	r_i	M_i	Virtual	Final
C0	-7	3	-22	1	1	0.5	0.9	11.5	4.537
C1	-9	-3.2	-15.9	1	1	0.5	0.87	3.82	-5.18
C2	-3	4.6	-7.9	1	1	0.5	0.85	2.29	-0.71
C3	2	10.4	-7.2	1	1	0.5	0.73	1.64	3.637
C4	13	21.9	1.9	1	1	0.5	0.88	1.27	14.27
C5	14	24	3.7	1	1	0.5	1	1.04	15.04
C6	1	11	-5.2	1	1	0.5	1.02	0.88	1.882
C7	9	13.2	5.7	1	1	0.5	0.95	0.76	9.764
T1	-2	0.2	-4.1	1	1	0.5	0.88	0.67	-1.33
T2	-11	-8.8	-13.1	1	1	0.5	1.02	0.6	-10.4
T3	-14	-11.8	-16.1	1	1	0.5	1.03	0.55	-13.5
T4	-1	1.2	-3.1	1	1	0.5	1.05	0.5	-0.5
T5	-8	-5.8	-10.2	1	1	0.5	1.07	0.46	-7.54
T6	-2	-0.3	-3.7	1	1	0.5	1.08	0.85	-1.15
T7	-8	-6.4	-9.6	1	1	0.5	0.6	1.19	-6.81
T8	2	3.5	0.7	1	1	0.5	0.7	1.11	3.109
T9	1	2.1	0	1	1	0.5	0.72	1.04	2
T10	16	18.4	13.8	1	1	0.5	0.97	0.98	16.98
T11	9	15.5	6	1	1	0.5	0.93	0.93	9.929
T12	18	25.4	14.2	1	1	0.5	0.85	0.88	18.88
L1	15	23.2	10.7	1	1	0.5	0.83	0.84	15.84
L2	-1	8.7	-4.9	1	1	0.5	0.81	0.8	-0.2
L3	-12	-0.9	-14.9	1	1	0.5	0.8	0.76	-11.2
L4	-20	-6.2	-23.9	1	1	0.5	0.7	0.73	-19.3
L5	3	14	-1.9	1	1	0.5	0.7	0.7	3.702

Table 2. The parameter setting in the Force Decomposition Method

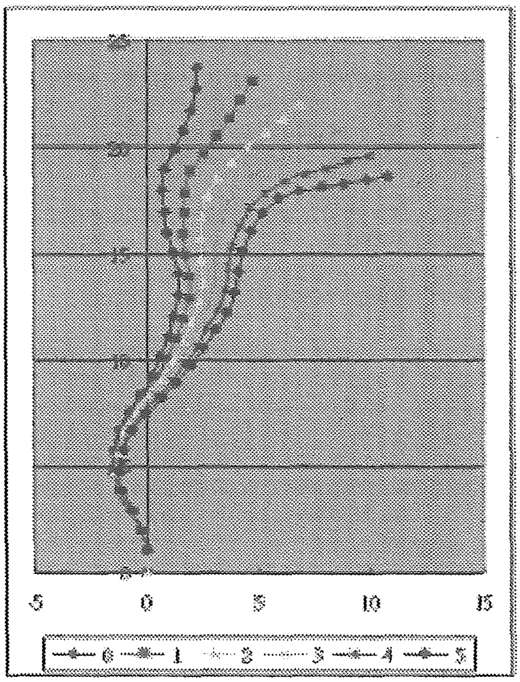


Figure 10. Continuous force exertion on T6 in the Force Decomposition Method

In order to become familiar with the operations of our kinematics system, an intuitive and convenient interface is essential. We provide an interactive user interface with pop-up functions and help documents for users. With the suggestions of therapists and patients, our three methods of biometrics contain 72, 18, and 96 parameters respectively. It is not always easy for a junior doctor to obtain the optimal parameters of our system. Besides, it takes time for people to adapt to 3-D input devices. Nevertheless, broadly speaking, users can interact with objects in a virtual environment, and this VR-based mechanism indeed presents a more vivid appearance than in traditional ways.

In an objective analysis, we know it is never easy to compare the actual movement of vertebrae with our experimental results. We still can ask the question of "Is the spinal movement natural?" Though spatial constraints can help us regulate the movement of the vertebrae, there is no guarantee of balance. Some extreme positions may exist without the violation of constraints. We need more expert knowledge to provide us with guidelines of spinal movements.

5 Conclusions

Practical research on biomedicine and biomechanics can not only improve quality of life, but also help the progress of clinical medicine. With powerful graphical capabilities, many visualization tasks can be presented at a lower cost. Our kinematics simulation system provides an educational platform for educating people in better understanding their body movements. We draw our conclusions as follows:

1) We proposed a prototype of VR-based kinematics simulation system. The three main components of our system include Geometric Modeling, Virtual Environment Arrangement, and Interactive Behavior Definition. The structures of highly modularized components enable more flexibility in implementation. As a result, all geometric models and biometrics can easily adapt to other applications.

2) We designed the biometrics of spinal movement by using three methods. The Decrement Method and the Segmented Decrement Method are based on hypothesis, whereas the Force Decomposition Method employs physical rules in statics. The first two methods also serve the function of moment assignment to be used in the third method.

3) Our system not only has intuitive and interactive properties, but also provides a learning platform for kinematics simulation. The simulation can be examined repeatedly, and the participants can arbitrarily change their views to meaningful positions. These characteristics are useful in educational training and experiments.

The goal of our spinal kinematics system is to approximate real spinal movement as close as possible. Actually, the most sophisticated part of our system is in biomechanics itself. The integration of the musculoskeletal system and the nervous system is so sophisticated that it is not feasible in our current implementation. However, our VR-based spinal kinematics simulation does provide a practical method for education and training.

References

[1] Grigore Burdea, and Philippe Coiffet, "Virtual Reality Technology", ISBN 0-471-08632-0.

[2] Martin R. Stytz, "Distributed Virtual Environments," *IEEE CG&A*, Vol. 16, No. 3, pp. 19-31, May 1996.

[3] Larry F. Hodges, Rob Kooper, Thomas C. Meyer, Barbara O. Rothbaum, et al., "Virtual Environments for Treating the Fear of Heights," *IEEE Computer*, Vol. 28, No. 7, pp. 27-34, 1995.

[4] Larry F. Hodges, Benjamin A. Watson, and G. Drew Kessler, "Virtually Conquering Fear of Flying," *Virtual Reality*, pp. 42-49, Nov 1996.

[5] Ronald L. Huston, "Multibody Dynamics", ISBN 957-00-6167-7.

[6] Ronald L. Huston and Yang Sheng Liu, "Optimal Human Posture – Analysis of a Waitperson Holding a Tray."

[7] dVS User Guide, dVISE User Guide, Geometry Tools User Guide

[8] Enrico Puppo and Roberto Scopigno, "Simplification, LOD, and Multiresolution Principles and Applications."

[9] Kevin J. Renze and James H. Oliver, "Generalized Unstructured Decimation," *IEEE CG&A*, pp. 24-32, Nov 1996.

[10] Jonathan C. Carr, W. Richard Fright, and Richard K. Beatson, "Surface Interpolation with Radial Basis Functions for Medical Imaging," *IEEE Trans. on Medical Imaging*, Vol. 16, No. 1, pp. 96-107, Feb 1997.

[11] Anthony Yezzi, Jr., Satyanad Kichenassamy, Arun Kumar, et al., "A Geometry Snake Model for Segmentation of Medical Imagery," *IEEE Trans. on Medical Imaging*, Vol. 16, No. 2, pp. 199-209, April 1997.

[12] Aurelio Cappozzo, Angelo Cappello, Ugo Della Croce, and Francesco Pensalfini, "Surface-Marker Cluster Design Criteria for 3-D Bone Movement Reconstruction," *IEEE Trans. on Biomedical Engineering*, Vol. 44, No. 12, pp. 1165-1174, Dec 1997.