

Simulating Dynamics of Thoracolumbar Spine Derived from LifeMOD under Haptic Forces

K. T. Huynh, I. Gibson, W. F. Lu, and B. N. Jagdish

Abstract—In this paper, the construction of a detailed spine model is presented using the LifeMOD Biomechanics Modeler. The detailed spine model is obtained by refining spine segments in cervical, thoracic and lumbar regions into individual vertebra segments, using bushing elements representing the intervertebral discs, and building various ligamentous soft tissues between vertebrae. In the sagittal plane of the spine, constant force will be applied from the posterior to anterior during simulation to determine dynamic characteristics of the spine. The force magnitude is gradually increased in subsequent simulations. Based on these recorded dynamic properties, graphs of displacement-force relationships will be established in terms of polynomial functions by using the least-squares method and imported into a haptic integrated graphic environment. A thoracolumbar spine model with complex geometry of vertebrae, which is digitized from a resin spine prototype, will be utilized in this environment. By using the haptic technique, surgeons can touch as well as apply forces to the spine model through haptic devices to observe the locomotion of the spine which is computed from the displacement-force relationship graphs. This current study provides a preliminary picture of our ongoing work towards building and simulating bio-fidelity scoliotic spine models in a haptic integrated graphic environment whose dynamic properties are obtained from LifeMOD. These models can be helpful for surgeons to examine kinematic behaviors of scoliotic spines and to propose possible surgical plans before spine correction operations.

Keywords—Haptic interface, LifeMOD, spine modeling.

I. INTRODUCTION

THE spine is one of the most important and indispensable structures in the human body. It allows complex motions whilst providing stability and protection for the spinal cord during a variety of loading conditions. However, it is a very vulnerable part of our skeleton that is open to many medical problems. People with sedentary jobs may spend hours sitting in a chair in a relatively fixed position, with their lower back forced away from its natural lordotic curvature. This prolonged sitting was reported to be linked with lower back problems. Sustained lumbar flexion [1] and prolonged static loads [2] suggest possible risks linking prolonged sitting with

lower back disorders. 80% of people in the United States will have lower back pain at some point in their life [3]. Back pain is strongly associated with degeneration of intervertebral discs [4]. As compared to lower back pain, scoliosis is a less common but a more complicated spinal disorder. Scoliosis is a congenital three-dimensional deformity of the spine and trunk affecting between 1.5% and 3% of the population. In severe cases, surgical correction is required to straighten and stabilize the scoliosis curvature. Many investigations have studied the human spine in attempts to broaden our understanding and to develop new implants and new surgical strategies for treating these spinal diseases.

Recently, many software applications have been developed for impact simulation and analysis, ergonomics, comfort study, biomechanical analysis, movement simulation and analysis. These tools are very useful for simulating the man-machine interaction. LifeMOD from Biomechanics Research Group is a leading simulation tool that has been designed for this purpose. The LifeMOD Biomechanics Modeler is a plug-in module to the ADAMS (Automatic Dynamic Analysis of Mechanical Systems) physics engine, produced by MSC Software Corporation to perform multi-body analysis. It provides a default multi-body model of the human body that can be modified by changing anthropometric sizes. The created human body may be combined with any type of physical environment or system for full dynamic interaction. The results of the simulation are human motion, forces exerted by the muscles, and the stresses or strains at the desired location of the human body [5]. In the multi-body dynamic models, the vertebral bodies are modeled as rigid bodies while the interconnecting tissues, such as intervertebral discs and facet joints, are represented by different joint models or spring damper elements. Mathematical equations representing the behavior of spring-damper elements govern the kinematic and kinetic response of the models to externally applied forces like those applied by muscle tissue [6]. LifeMOD was used as a multi-body dynamic simulation platform in numerous modeling researches. A dynamic simulation of the cervical spine containing a disc implant was performed using LifeMOD to understand the intradiscal forces/pressures, bending moments and vertebral body rotation [7]. In a similar manner, a human-wheelchair musculoskeletal model was generated with LifeMOD to analyze the cervical spine injury of wheelchair user regarding frontal and side impacts [8]. In a research to conduct complex biomechanical analysis of

K. T. Huynh is with the Department of Mechanical Engineering, National University of Singapore, Singapore 117576 (Tel: 65-6516-4644; e-mail: huynhkimtho@nus.edu.sg).

I. Gibson is with the Department of Mechanical Engineering, National University of Singapore, Singapore 117576 (e-mail: mpegi@nus.edu.sg).

W. F. Lu is with the Department of Mechanical Engineering, National University of Singapore, Singapore 117576 (e-mail: mpelwf@nus.edu.sg).

B. N. Jagdish is with the Department of Mechanical Engineering, National University of Singapore, Singapore 117576 (e-mail: mpebnj@nus.edu.sg).

surgical gesture using LifeMOD, the muscle-skeleton model was integrated with motion capture in a system designed to analyze the surgeon's skill. The loads on bones, fatigue on muscles and ergonomics of surgical instruments can also be assessed in this simulation [9].

With the advancement of science, a novel technique, referred to as haptics, has been applied in numerous virtual reality environments to increase the levels of realism. Haptics has been investigated at length and widely applied to medical education and surgical simulations, such as for surgical planning and laparoscopic surgical training. Haptic interfaces provide touch feedback to operators through the PHANToM robotic device [10], thus simulation with haptic feedback may offer better realism compared to those with only a visual interface. For example, the Virtual Haptic Back, from Ohio University, is a significant teaching aid in palpatory diagnosis (detection of medical problems via touch) [11]. The Virtual Haptic Back simulates the contour and compliance properties of human backs, which are palpated with two haptic interfaces. In [12], a haptic feedback lumbar puncture simulator was devised to provide a safe method of training medical students for an actual lumbar puncture procedure on a patient. Lumbar punctures are complex, precise procedures done to obtain cerebro-spinal fluid from a patient for diagnostic purposes. Errors resulting from inadequate training can result in serious outcomes. The haptic simulator hopefully could provide good preliminary training for the lumbar puncture process. Haptic applications are also found in spine surgery telerobotic systems [13]. Haptic feedback can guide operators during the execution of complex 5 degrees of freedom surgical teleoperation tasks.

The objective of our paper is to describe a haptic interface for a thoracolumbar spine model whose dynamic properties are obtained from LifeMOD. By simulating in a haptically integrated graphical environment, the users (surgeons, trainers) can experience more intuitive interaction since the spine model can be manipulated by touch as well as sight. The model can be used by orthopaedic surgeons to study the dynamic behavior of spines, the effect of different forces on the spine, and the changes of spine curvature resulting from long-term seating in chairs.

II. SYSTEM FRAMEWORK

Our system is composed of three components: a) detailed spine modeling and simulation in LifeMOD; b) generating a thoracolumbar spine with complex geometry of vertebrae using the graphic interface HOOPS; c) haptic simulation and analysis of the spine model. Fig. 1 shows the architecture of the system in our study.

As can be seen in Fig. 1, majority of our current work is done in the LifeMOD environment. Initially, a default base human model is generated. Then, spine segments are further refined into individual vertebra segments to obtain more reasonable and precise locomotion of the spine during simulation. Muscle attachments need to be reassigned to

specific corresponding segments with the same physical attachment locations. To fully describe six degrees of freedom of spinal joints such as intervertebral discs, bushing elements are used to represent the discs instead of rotational joints. Various ligaments are then attached to vertebra segments for further stabilizing of the spine. After simulating in LifeMOD, dynamic properties of the spine (such as displacement, velocity etc.) can be computed based on the external forces applied. The relationships between these properties and external forces are expressed graphically in terms of polynomial functions. These relationships are then imported into a graphic interface named HOOPS which links the haptic interface with the spine model. To obtain better observation of the locomotion of the spine, a thoracolumbar spine model with complex geometry of vertebrae is generated from 3D laser scanning and used instead of the spine model generated in LifeMOD. By integrating with the haptic interface, users can interact with the spine model more realistically through the sense of touch. Also, the users can apply external forces generated from the haptic devices to the spine model to examine the dynamic behavior of the spine.

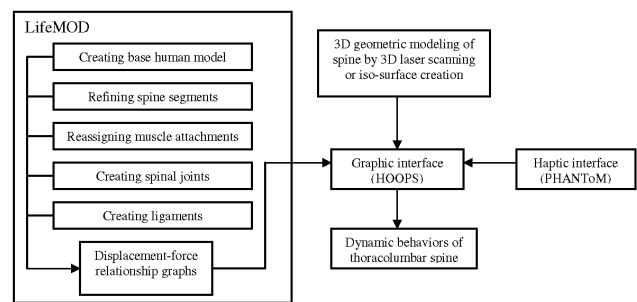


Fig. 1 System overview

III. METHOD

A. Detailed Spine Modeling in LifeMOD

1) Creating the Base Model

The usual procedure of generating a human model is to create a complete set of body segments followed by redefining the fidelity of the individual segments. The body segments of a complete standard skeletal model are first generated by LifeMOD depending on the user's anthropometric input. The model used in this study was a median model created from the GeBod anthropometric database. By default, LifeMOD generates 19 body segments represented by ellipsoids. Since the spine region is of interest, the arms and legs will be removed from the human model. Then, some fixed joints and muscles are generated for the human model. Fig. 2 shows the base model in our study.

2) Refining the Spine Segments

From the base human model, the segments may be broken down into individual bones for greater model fidelity. Every bone in the human body is included in the generated skeletal model as a shell model. To discretize the spine region, the standard ellipsoidal segments representing the cervical (C1-

C7), thoracic (T1-T12) and lumbar (L1-L5) vertebrae are firstly removed. The individual vertebra segment is then given a name, CM location (designates the center of mass) and orientation (for the alignment of the inertia tensor to its reference axis system). The working grid of the model has to be established to allow more accurate estimation of CM location and orientation. Next, mass properties are estimated using ellipsoids. Fig. 3 displays the refining process of the cervical region. Based on this procedure, the 24 vertebrae in the cervical, thoracic and lumbar regions are further discretized into individual ellipsoidal segments for simulations as can be seen in Fig. 4.

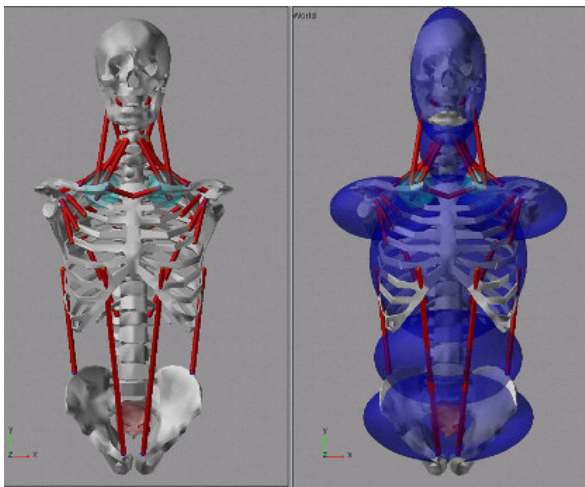


Fig. 2 The base human model

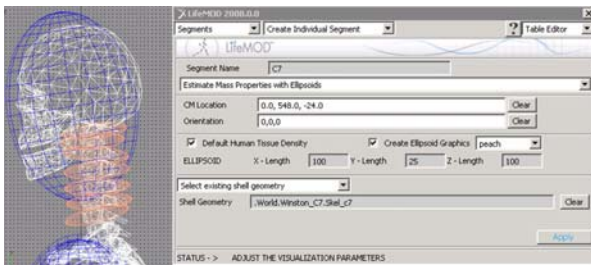


Fig. 3 Refining process of the cervical spine

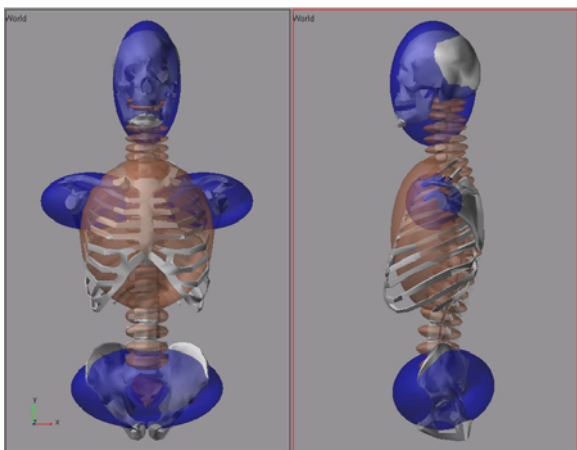


Fig. 4 Front and side view of the complete discretized spine

3) Reassigning Muscle Attachments

The muscles are attached to the respective bones based on geometric landmarks on the bone graphics. With the new vertebra segments created, the muscle attachments to the original segment must be reassigned to be more specific to the new vertebra segments. The physical attachment locations will remain the same. Fig. 5(a) and (b) shows the anterior and posterior view of neck/trunk muscle set. Table I lists attachment locations of all these muscles.

TABLE I
 ANTERIOR AND POSTERIOR VIEW OF NECK AND TRUNK MUSCLE SET

Index	Muscle	Attach proximal	Attach distal
1	Rectus abdominis	Sternum	Pelvis
2	Obliquus externus	Ribs	Pelvis
3	Scalenus medius	C5	Ribs
4	Scalenus anterior	C5	Ribs
5	Sternocleidomastioideus	Head	Scapula
6	Erector spinae 2	L2	Pelvis
7	Erector spinae 3	T7	L2
8	Erector spinae 1	T7	Pelvis
9	Scalenus posterior	C5	Ribs
10	Splenius cervicis	Head	C7
11	Splenius capitis	Head	T1

4) Creating the Spinal Joints

It is necessary to create individual non-standard joints between newly created vertebrae. The rotational joints available in LifeMOD cannot be used to model intervertebral discs since they act as tri-axis hinge joints. To obtain six degrees of freedom of intervertebral discs (flexion/extension, bending, torsion, tension/compression, anterior/posterior shearing and lateral shearing), bushing elements will be utilized instead. Such properties as stiffness, damping and angular limits of intervertebral discs will be assigned to the bushing elements. These properties can be found in [14]-[19]. The average segmental ranges of spinal motion are listed in Table II. Table III and IV show linear and torsional stiffnesses of intervertebral joints in different regions of the spine. Intervertebral discs are then represented by busing elements as shown in Fig. 6.

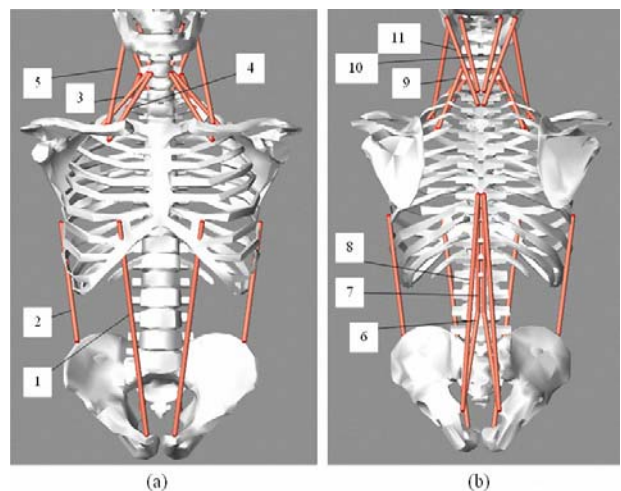


Fig. 5 Anterior and posterior view of neck and trunk muscle set

TABLE II

AVERAGE SEGMENTAL RANGE OF MOTION DEGREES AT EACH SPINE LEVEL				
Level	Flexion	Extension	Lateral bending	Torsion
Occ-C1	13	13	8	0
C1-C2	10	9	0	47
C2-C3	8	3	10	9
C3-C4	7	9	11	11
C4-C5	10	8	13	12
C5-C6	10	11	15	10
C6-C7	13	5	12	9
C7-T1	6	4	14	8
T1-T2	5	3	2	9
T2-T3	4	4	3	8
T3-T4	5	5	4	8
T4-T5	4	4	2	8
T5-T6	5	5	2	8
T6-T7	5	5	3	8
T7-T8	5	5	2	8
T8-T9	4	4	2	7
T9-T10	3	3	2	4
T10-T11	4	4	3	2
T11-T12	4	4	3	2
T12-L1	5	5	3	2
L1-L2	8	5	6	1
L2-L3	10	3	6	1
L3-L4	12	1	6	2
L4-L5	13	2	3	2
L5-S1	9	5	1	1

TABLE III

TYPICAL LINEAR STIFFNESS VALUES OF THE SPINE (N/MM)			
	Cervical	Thoracic	Lumbar
Compression	1317	1250	600 – 700
Lateral shear	33	100	100 – 200
Anterior posterior shear	33	900	100 – 200

TABLE IV

AVERAGE TORSIONAL STIFFNESS VALUES FOR THE ADULT HUMAN SPINE (N.MM/DEG)			
Spine level	Flexion/Extension	Lateral bending	Axial torsion
Occ-C1	40/20	90	60
C1-C2	60/50	90	70
C2-C7	400/700	700	1200
T1-T12	2700/3300	3000	2600
L1-L5	1400/2900	1600	6900
L5-S1	2100/3000	3600	4600

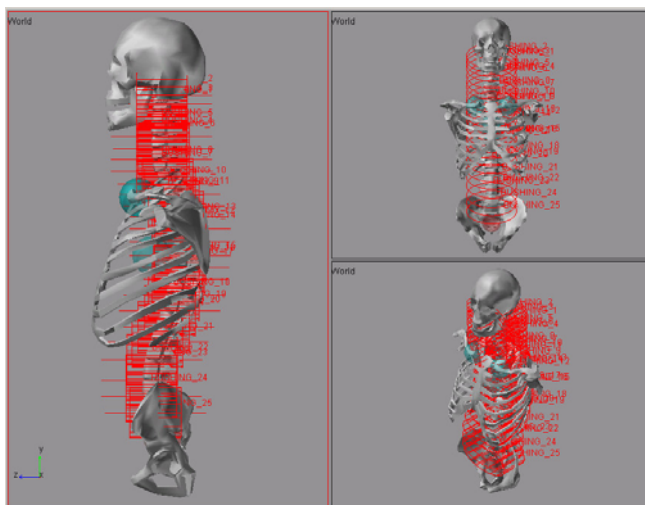


Fig. 6 Bushing elements representing for intervertebral discs

5) Creating Ligamentous Soft Tissues

To stabilize the spine model, interspinous, flaval, anterior longitudinal and capsule ligaments will be created. Fig. 7 displays side and rear view of ligaments attached to vertebrae in the cervical region of the spine. These ligaments surrounding the spine will guide segmental motion and contribute to the intrinsic stability of the spine by limiting excessive motion. The stiffness of these ligaments is referenced from [20] and listed in Table V.

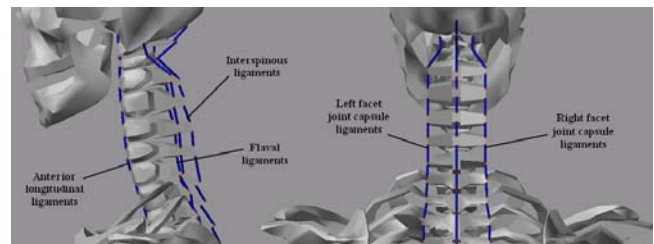


Fig. 7 Side and rear view of ligaments in the cervical region

TABLE V
 STIFFNESS VALUES OF VARIOUS SPINE LIGAMENTS (N/MM)

Interspinous ligaments	Ligamentum flavum	Anterior longitudinal ligament	Joint capsule
7	23.3	17	32.5

B. Simulating and Establishing Displacement-Force Relationships

After the detailed spine generating is completed, some constraints are imposed on the spine model. The pelvis and the vertebra T1 is fixed in 3D space. In the sagittal plane of the spine, constant forces are then applied to a certain vertebra from the posterior to anterior in z direction during simulation. In our current study, range of force magnitude is limited up to 600N. The force magnitude is gradually increased with an equal increment in subsequent simulations. Corresponding to each value of force, dynamic characteristics (e.g. displacement, rotation so on) can be automatically obtained using the plots in LifeMOD as a reference. Fig. 8 shows a simulation process and plots of dynamic properties of each vertebra in LifeMOD under external force applying to the vertebra T7. Since the main parameter is the displacement in the z direction, other dynamic properties are recorded at a time, when the translational distance of the vertebra in z direction is maximum. Based on these recorded dynamic properties, displacement-force relationships can be interpolated using the least-squares method and expressed in terms of polynomial functions. These relationships will be then imported into the HOOPS graphic interface and used when integrating with the haptic interface.

C. Thoracolumbar Spine Modeling in HOOPS

Since the geometry of the spine model in LifeMOD is very simple and importing this geometry into HOOPS is quite troublesome, a thoracolumbar spine model with complex geometry of vertebrae is used in this case to observe better the

locomotion of the spine. This spine model is generated by obtaining detailed polygonal mesh models of the vertebrae which are digitized from a resin spine prototype (Budget Vertebral Column CH-59X Life Size 29" Tall) through 3D laser scanning. Fig. 9 shows different views of this thoracolumbar spine model in HOOPS. After this stage, the graphic interface will be integrated with the haptic interface mentioned in detail in the next section to run haptic simulation for studying the dynamic behavior of the spine.

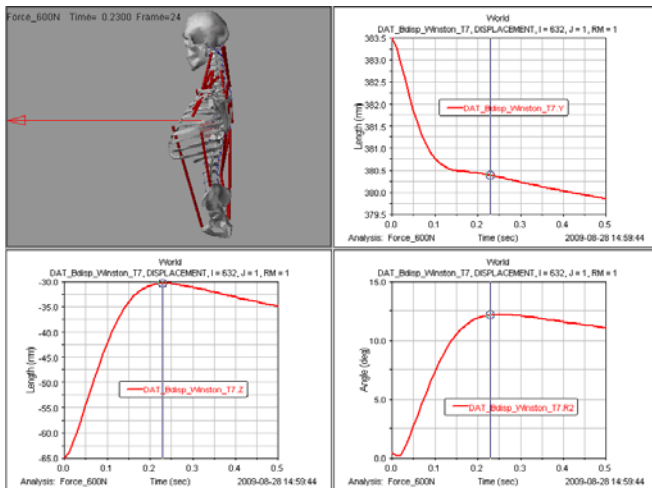


Fig. 8 Dynamic simulation process in LifeMOD

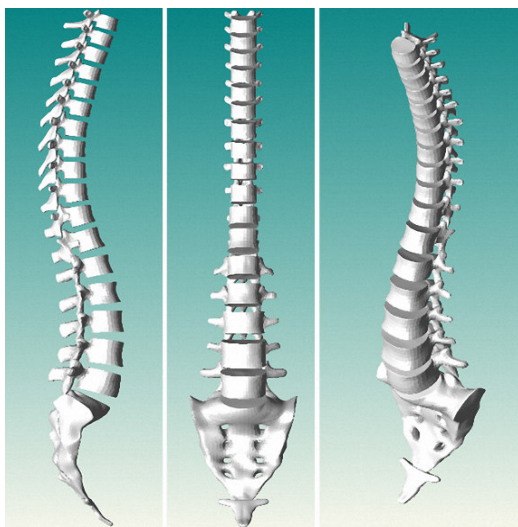


Fig. 9 Different views of thoracolumbar spine model in HOOPS

IV. HAPTIC INTERFACE

Haptics is a novel technique that has been applied in numerous virtual reality applications recently. Haptic interfaces require a high update rate of 1000 Hz to maintain force stability. This will help users to feel almost any shape with much realism. Otherwise, with lower update rates, virtual surfaces of objects will feel softer or, even worse, the haptic devices vibrate. Fig. 10 shows a haptic interface in use.

Haptic interfaces use haptic rendering algorithms to enable users to interact with virtual objects more intuitively through

devices like the PHANTOM. In our study, the haptic rendering process has two stages: the rigid stage and the compliant stage. Without pressing the PHANTOM stylus button, no external forces apply to the thoracolumbar spine model. The spine model becomes rigid in this stage. The user can touch and explore the whole spine model without making it deform. The algorithm used in the rigid stage is the point to triangular mesh haptic rendering method (point-wall method). After the user locates a vertebra where he/she wishes to apply forces from the posterior to anterior in the sagittal plane, they can then press the PHANTOM stylus button and push or drag the vertebra to make the whole spine model move. Once the stylus button is pressed, the system switches to another haptic rendering algorithm that uses the stretched-spring model. A virtual spring is set up connecting the vertebra and the haptic cursor. The spring has two hook points: one is on the vertebra and the other is on the haptic cursor. Both of the hook points displace during spine locomotion. The force magnitude is determined by the length of the virtual spring and stiffness while the force direction is in the positive direction of the z axis.



Fig. 10 Haptic interface in use

V. RESULTS

After the haptic interface is integrated into the graphic interface, haptic simulation can be executed. When the stylus button of the PHANTOM device is pressed, the users generate external forces and apply them to a specific vertebra of the spine model. Based on the force magnitudes, dynamic properties of each vertebra (such as translation, rotation) can be calculated via the interpolated polynomial functions of displacement force relationships. To obtain better understanding about these relationships, Fig. 11 to 17 show the plots of relative translation in y and z direction as well as relative rotation about the x axis when external forces are applied to vertebra T7. In these plots, each set of markers is a set of data points corresponding to each vertebra obtained from simulations in LifeMOD. The continuous lines correlate well with each set of data points and are interpolated by using the least-squares method and expressed in terms of polynomial functions.

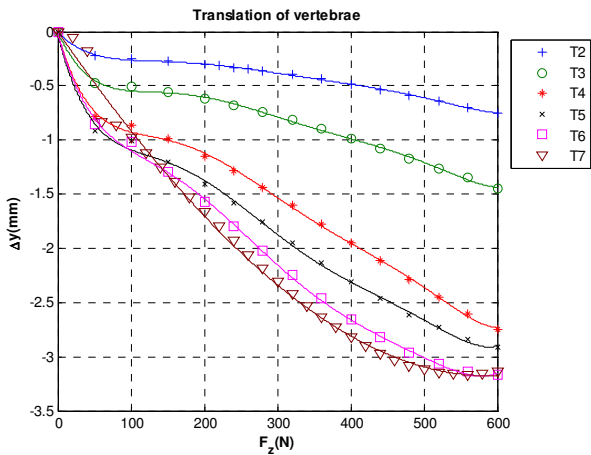


Fig. 11 Relative translation in y direction versus external force from T2 to T7

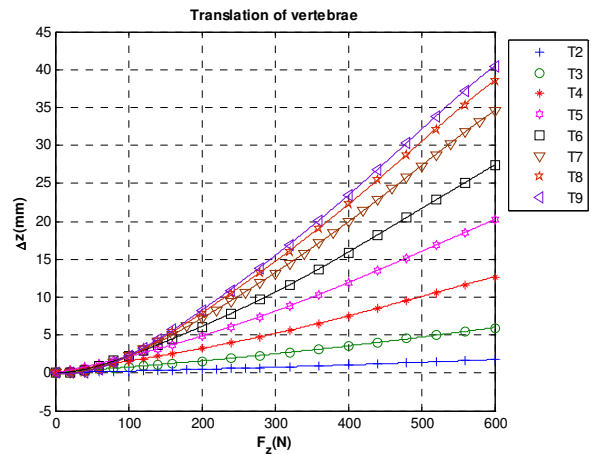


Fig. 14 Relative translation in z direction versus external force from T2 to T9

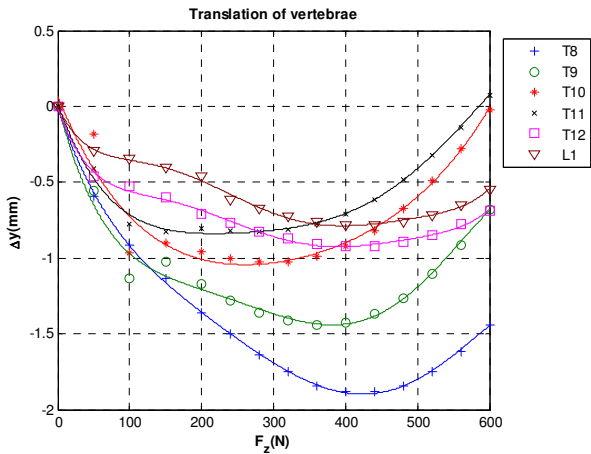


Fig. 12 Relative translation in y direction versus external force from T8 to L1

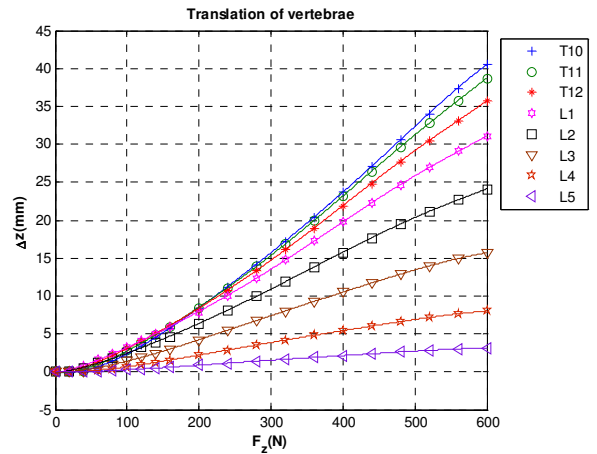


Fig. 15 Relative translation in z direction versus external force from T10 to L5

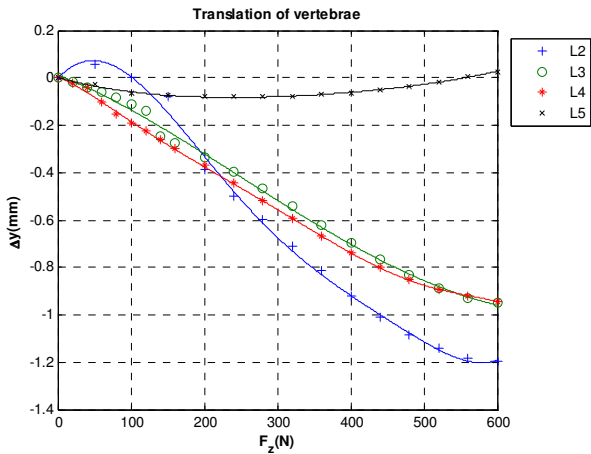


Fig. 13 Relative translation in y direction versus external force from L2 to L5

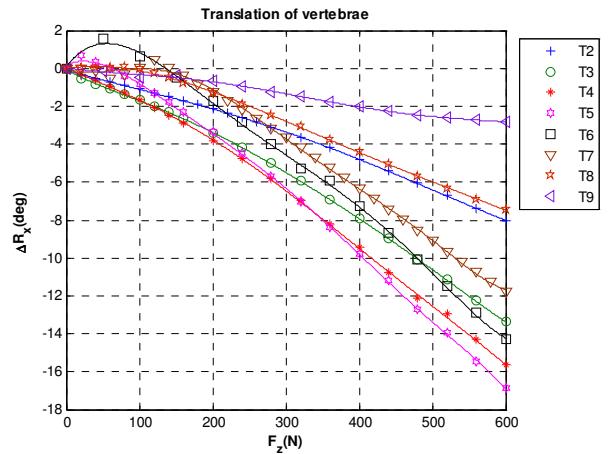


Fig. 16 Relative rotation about x axis versus external force from T2 to T9

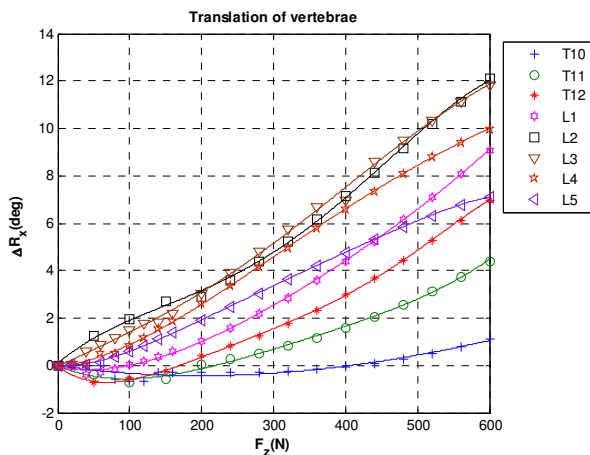


Fig. 17 Relative rotation about x axis versus external force from T9 to L5

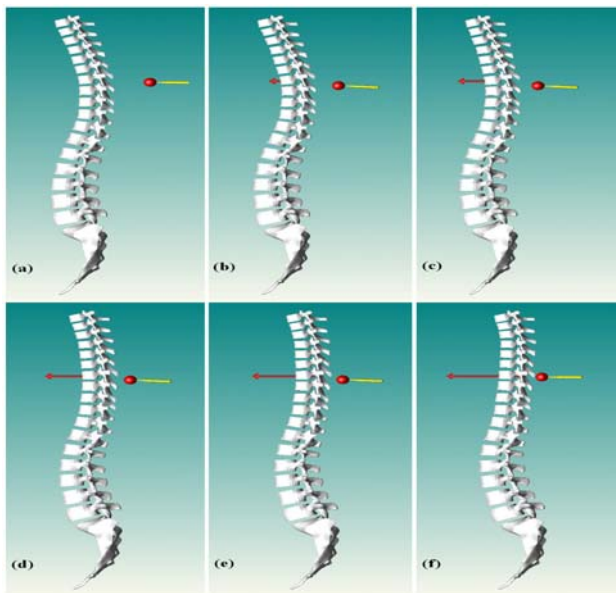


Fig. 18 Haptic simulation process in HOOPS

Fig. 18 shows a series of continuous movements of the thoracolumbar spine model under external forces acting on the vertebra T7. As can be seen from Fig. 18, T9 and T10 are two vertebrae moving furthestmost in the z direction when the applied force reaches a maximum value. Vertebrae T2 to T9 rotate clockwise whereas vertebrae T10 to L5 rotate counterclockwise. Since rotational speed of lower vertebra is greater in the region from T2 to T5 and smaller in the region from T5 to T9, intervertebral discs corresponding with these two regions are under flexion and extension respectively. Meanwhile, relative downward translation in y direction and counterclockwise rotation angle increasing from T10 to L3 causes tension and extension of intervertebral discs in this region. Contrary to this region, intervertebral discs from L3 to L5 are under compression and flexion due to decreasing magnitudes of the relative downward translation in the y direction as well as the rotation angle.

VI. DISCUSSION

Since the cervical, thoracic and lumbar regions of the default 19-segment multi-body model generated in LifeMOD are represented by three ellipsoidal segments, the movement of the spine cannot be depicted correctly and looks somewhat unrealistic. Also, this default model is unable to apply external forces to a specific desired vertebra and to determine the load on each intervertebral disc. Hence, this paper presented a detailed spine model where the model's spine vertebrae are discretized into individual ellipsoidal segments. With this detailed spine model, it is possible to apply external forces to individual vertebrae and thus the locomotion of the spine will be more reasonable and precise. In addition, the individual joints created between vertebrae using bushing elements can also provide us with the load acting on the intervertebral discs. For example, Fig. 19 shows the forces acting on intervertebral disc between T8 and T9 vertebrae in x, y and z directions. Moreover, unlike the default model, the stiffness and range of motion of the intervertebral discs can be specified and the effects of external forces on the curvature of the spine are observed. In other words, different dynamic characteristics of all vertebrae can be obtained based on the external forces applied.

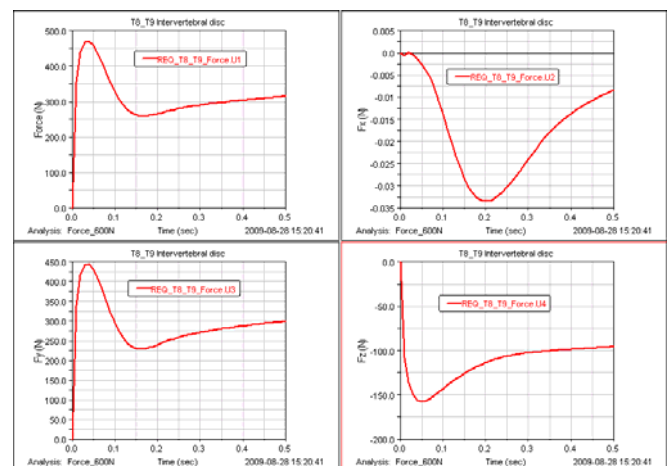


Fig. 19 Load on T8-T9 intervertebral disc

There are still some limitations remaining in our current study. One of the major limitations is the modeling of the thoracic spine region. For the thoracic spine region, the twelve pairs of ribs articulate posteriorly with the spine at the costovertebral joints. The presence of the ribcage corresponds to the higher stiffness experienced at the thoracic spine. However, in this study, it is not possible to create the 12 pairs of costovertebral joints between the ribcage and the corresponding thoracic vertebrae. The reason is that the objects in LifeMOD are modeled as completely rigid bodies and therefore the deformation properties cannot be assigned to them. Simultaneously connecting the ribcage segment to multiple vertebra segments can result in software errors in the simulation process since the ribcage will deform during locomotion. To solve this problem, the ribcage segment is

linked to the thoracic spine region only at the 6th thoracic vertebra.

VII. CONCLUSION

We have presented detailed spine modeling in LifeMOD and integrated the haptic interface into a HOOPS graphic simulation environment. A detailed spine model generated in LifeMOD will provide dynamic properties of all vertebrae and the haptic interface is used to apply external forces to a desired vertebra. During haptic simulation, users can interact with the spine model more realistically to study the dynamic behavior of the spine. The current study shows a preliminary picture of our ongoing work towards building and simulating bio-fidelity spine models based on LifeMOD software in a haptics integrated graphic environment.

Future developments of our work will include investigating dynamic characteristics of the spine model under external forces applied to the individual vertebrae in y and x-axis directions. Furthermore, every individual has its own unique spine structure. Default LifeMOD spine models cannot represent asymmetrical spine or patients with spinal deformities. However, since these default models are fully parameterized where input parameters (such as height, weight, sex, etc) can be easily varied, highly versatile models can be generated and conveniently tuned to suit various individual spines. In other words, different types of scoliotic spines models will be analyzed for conducting in-depth studies on the motion of these spines subjected to dynamic forces. These models can be useful for orthopaedic surgeons to examine kinematic behaviors of scoliotic spines, the effect of external forces on the spines, and the changes of spine curvature resulting from long-term seating in chairs.

REFERENCES

- [1] M. A. Adams, and P. Dolan, "Recent advances in lumbar spinal mechanics and their clinical significance," *Clin. Biomech.*, vol. 10, no. 1, pp. 3-19, Jan. 1995.
- [2] J. P. Callaghan, and S. M. McGill, "Low back joint loading and kinematics during standing and unsupported sitting," *Ergonomics*, vol. 44, no. 3, pp. 280-294, Feb. 2001.
- [3] B. Vallfors, "Acute, subacute and chronic low back pain: clinical symptoms, absenteeism and working environment," *Scand. J. Rehab. Med. Suppl.*, vol. 11, pp. 1-98, 1985.
- [4] K. Luoma, H. Riihimaki, R. Luukkonen, R. Raininko, E. Viikari-Juntura, and A. Lamminen, "Low back pain in relation to lumbar disc degeneration," *Spine*, vol. 25, pp. 487-492, 2000.
- [5] K. W. Lee, "CAD system for human-centered design," *Computer-Aided Design & Applications*, vol. 3, no. 5, pp. 615-628, 2006.
- [6] H. S. Ahn, "A virtual model of the human cervical spine for physics-based simulation and applications," Ph.D dissertation, University of Tennessee, May 2005.
- [7] C. U. De Jongh, A. H. Basson, and C. Scheffer, "Dynamic simulation of cervical spine following single-level cervical disc replacement," in *Proceedings of the 29th Annual International Conference of the IEEE EMBS*, Lyon, France, 2007, pp. 4289-4292.
- [8] S. M. Kim, I. C. Yang, and M. P. Lee, "Cervical spine injury analysis regarding frontal and side impacts of wheelchair occupant in vehicle by LifeMOD," in *IFMBE Proceedings*, 2007, vol. 14, no.4, pp. 2521-2524.
- [9] F. Cavalloa, G. Megalia, S. Sinigagliaa, O. Toneta, P. Darioa, and A. Pietrabissa, "A step towards biomechanical analysis of surgeon's

gesture on Adams-LifeMOD platform," *Int. J. CARS*, vol. 2, no. 1, pp. 160-180, 2007.

- [10] SensAble.PHANTOMTM. Available: <http://www.sensable.com>
- [11] R. L. Williams, M. Srivastava, J. N. Howell, et al, "The virtual haptic back for palpatory training," in *Proceedings of the 6th International Conference on Multimodal Interfaces*, Pennsylvania, USA, 2004, pp. 191-197.
- [12] P. Gorman, T. Krummel, R. Webster, M. Smith, and D. Hutchens, "A prototype haptic lumbar puncture simulator," *Stud. Health Technol. Inform.*, vol. 70, pp. 106-109, 2000.
- [13] G. Boschetti, G. Rosati, and A. Rossi, "A haptic system for robotic assisted spine surgery," *IEEE Conference on Control Applications*, pp. 19-24, Aug. 2005.
- [14] Van C. Mow, and Wilson C. Hayes, *Basic Orthopaedic Biomechanics*. New York: Raven Press Ltd., 1991, ch. 8.
- [15] M. H. Berkson, A. L. Nachemson, and A. B. Schultz, "Mechanical properties of human lumbar spine motion segments - Part 2: responses in compression and shear; influence of gross morphology," *J. Biomech. Eng.*, vol. 101, pp. 52-57, 1979.
- [16] K. M. McGlashen, J. A. Miller, A. B. Schultz and G. B. Andersson, "Load displacement behavior of the human lumbo-sacral joint," *J. Orthop. Res.*, vol. 5, pp. 488-496, 1987.
- [17] S. P. Moroney, A. B. Schultz, J. A. Miller, and G. B. Andersson, "Load-displacement properties of lower cervical spine motion segments," *J. Biomech.*, vol. 21, pp. 769-779, 1988.
- [18] M. M. Panjabi, R. A. Brand, and Jr. White AA, III, "Mechanical properties of the human thoracic spine as shown by three-dimensional load-displacement curves," *J. Bone Joint Surg. Am.*, vol. 58, pp. 642-652, 1976.
- [19] A. B. Schultz, D. N. Warwick, M. H. Berkson, and A. L. Nachemson, "Mechanical properties of human lumbar spine motion segments. Part 1: Responses in flexion, extension, lateral bending and torsion," *J. Biomech. Eng.*, vol. 101, pp. 46-52, 1979.
- [20] N. Yoganandran, N. Kumaresan, and F. A. Pintar, "Biomechanics of the cervical spine. Part 2. Cervical spine soft tissue responses and biomechanical modeling," *Clin. Biomech.*, vol. 16, pp. 1-27, 2001.