Three-Dimensional Modeling and Finite Element Analysis of the Human Spine and Axial Skeletal System Under Dynamic

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Abstract: *A three dimensional model of the human axial skeletal structures was developed in order to perform Finite Element Analysis (FEA) on the spine under dynamic loads. Loading was applied to approximate real world traumatic kinetic events in order to study the response of the skeletal system, and to study the effect of loads on the spinal cord and brain.*

Keywords: Spine Modeling, Bone Structure, Dynamic Impact, Abaqus/Explicit

1. Introduction

Trauma to the spinal column can result in severe injury, often leading to paralysis or death. In order to facilitate the development more advanced means of protecting the brain and spine during traumatic kinetic events such as whiplash, an accurate predictive model of the spine, skull, brain, incorporating the appendicular skeleton is needed. Finite Element Analysis is a method of approximating the structure and mechanical properties of a system such as the spine, then simulating the response of the system to static and dynamic conditions.

Model Details

The model was created using HyperMesh, and was imported into Abaqus/Explicit for the Finite Element Analysis. The model consists of the pelvis, sacrum, coccyx, vertebra of the lumbar, thoracic, and cervical spine, skull, brain, spinal cord, ribs, arms, legs and clavicular. [Geometries were obtained online from GrabCAD.com]

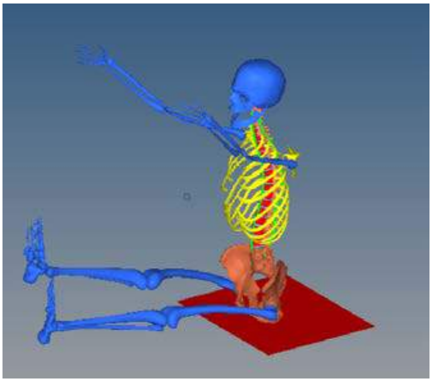

Figure 1. Figure of the Model Generated

The brain and skull models are divided into 4 parts. The skull is a shell mesh, with the material specified as “bone”. The shell element type used was S3 with a thickness of 0.5mm. The brain is divided into two parts: lower brain and upper brain. These parts are solid meshed with an element type of C3D4. The last part is a small rigid plate underneath the brain to maintain the placement of the brain, which we set the reference node on the skull. The plate is a one element mesh with an element type of R3D4. [Cammino et Al, 2016], [H.Y. Ling and S.H. Tan]

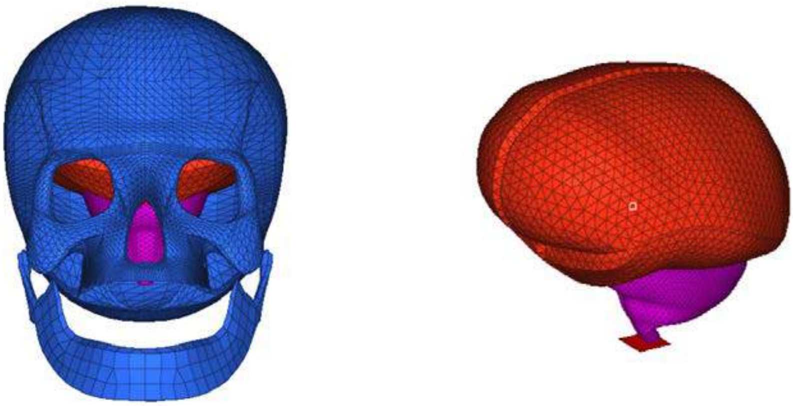

Figure 2. Model of the head and brain

The spine is divided into 5 parts: Cervical, thoracic, lumbar, sacral and coccyx. The lumbar area is divided into 5 parts: L1, L2, L3, L4 and L5. The pelvis file contains L4 and L5, along with the sacrum and coccyx. [Marta Kurutz, 2010], [Gong, et Al, 2014], [H.Y. Ling and S.H. Tan]

The elements of the spine are shown below in four different colors. The orange areas are the parts of the bone that contain the spinous and transverse processes of the vertebrae; these are as of the model are all deformable. The mesh was done using tetrahedral elements, with an element type C3D4 and the material type called “bone”. The grey areas are the spinal cords, which were put through the vertebras. These areas of the model are all deformable, too. The mesh was done using tetrahedral elements, with an element type C3D4. The areas shown in red are the parts of the bone area containing the body of the vertebrae, which are not very deformable. The element used for these parts is tetrahedral, and the element type is C3D4.This element type was defined rigid and not deformable in order to save computational time; the simulation will run faster due to this.

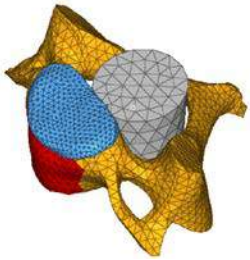

Figure 3. Section of the Spine Details

The blue areas of the spine are the disks. These are meshed using tetrahedral elements of second order. A second order element means there are extra nodes. And thus is a more exact element. The element type is C3D10M, and the material used are based on researched properties found in papers where testing was done on these materials. [Marta Kurutz, 2010], [Diamant et Al]

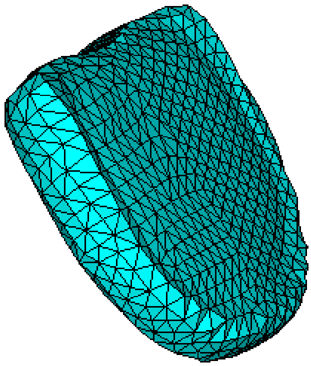

Figure 4. Model of the disk

Shown in green are the ligaments. There are 4 ligaments in the model: the Anterior Longitudinal Ligament (ALL), the Posterior Longitudinal Ligament (PLL) and two inter-transverse Ligaments (IL), one each on the right and left of the spine. The elements used for the ligaments are truss elements and the element type is T3D2. For the truss elements it is necessary to specify the cross sectional area, which for the purpose of running the simulation has been estimated to be 63.7mm for the ALL, 20 for the PLL and 20 for both IL.[More exact values will be needed to improve the accuracy of the model and any simulations.] [H.Y. Ling and S.H. Tan], [Volkan and Acar], [H.Y. Ling and S.H. Tan].

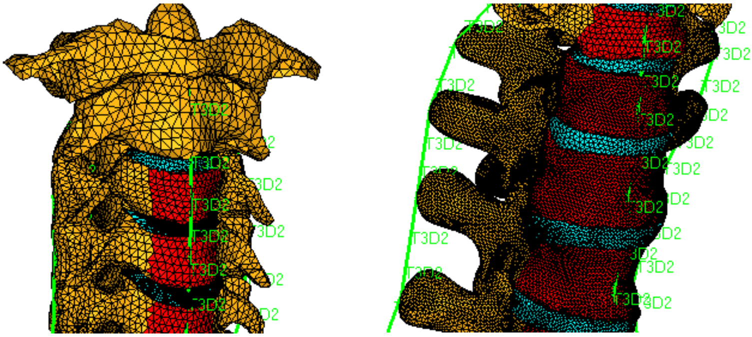

Figure 5. Details related to the spine model

The pelvis is a solid mesh using tetrahedral elements. All the elements are deformable and the type of elements used is C3D4, to save on computational time. The material defined for the whole pelvis is bone related.

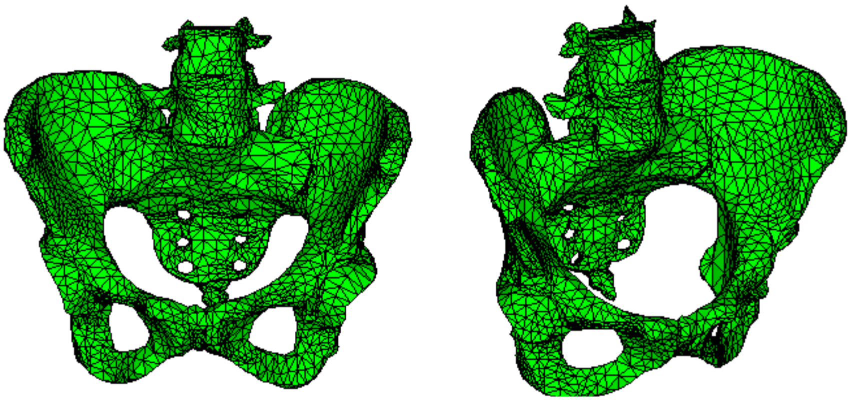

Figure 6. Model of the pelvis

The arms, legs, and clavicle are all defined as rigid bodies, in order to save computational time, but can be easily turned into deformable bodies.

Figure 7. Model of the arms and legs

Table1. Element Type of Each Component

Component	Element Type	Component	Element Type
Pelvis	C3D4	Spinal Cord	C3D4
Ligament	T3D2	Disk	C3D10M
Arm	R3D4/R3D3	Spinal Bone	R3D3
Head	S3	Jaw	S3/S4
Brain	C3D4		
Leg	R3D4/R3D3		
Rib	C3D4		

2. Materials

Numerous references are available to describe the material properties of the various structures of the spine and the disk as shown below. We also need to account special circumstances with disk modeling. [Migaczl et Al] and [Araujo et Al]

Table 2. Materials of Each Component

Element	Material Density (g/mm^3)	Poisson's Ratio	Modulus (MPa)	Reference
Pelvis	0.00175	0.3	12000	Li-Xin Guo, 2009
Skull	0.00175	0.3	12000	Li-Xin Guo, 2009
Brain	0.00105	0.48	0.06	
Cervical Vertebrae	0.00175	0.3	12000	Li-Xin Guo, 2009
Thoracic Vertebrae	0.00175	0.3	12000	Li-Xin Guo, 2009
Lumbar Vertebrae	0.00175	0.3	12000	Li-Xin Guo, 2009
Intervertebral Disk	0.01	0.45	42	Zhiqiang Gong , 2014
Spinal Cord	0.01	0.494	1.4	Mazuchowski, 2003
Anterior Longitudinal Ligament	0.01	0.4	20	Zhiqiang Gong, 2014
Posterior Longitudinal Ligament	0.01	0.4	20	Zhiqiang Gong , 2014
Intertransverse Ligament	0.01	0.4	20	Zhiqiang Gong , 2014

*****The actual Young's modulus of Disk is 4.2. while in realistic situation, it will be pre-compressed and, to simplify, we change the disk's Young's modulus from 4.2 to 42.

3. Results and Analysis

A simple drop on the ground of the system is performed using ABAQUS/Explicit. As shown in the figure below, the body is placed close to the ground and given an initial velocity to simulate impact to the ground from given heights.

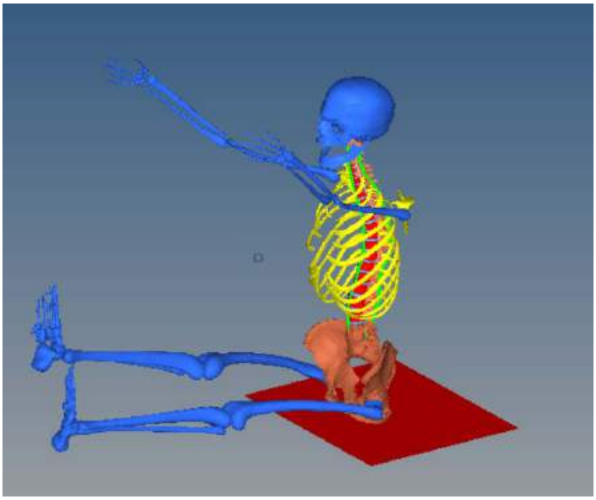

Figure 8. Figure of the Entire Model Hiting the Ground

The analysis is finally completed in ABAQUS/Explicit and results are shown in the following figures.

Figure 9. Strain contours on the Spinal Cord

Figure 10. Stress contours on the Spinal Cord

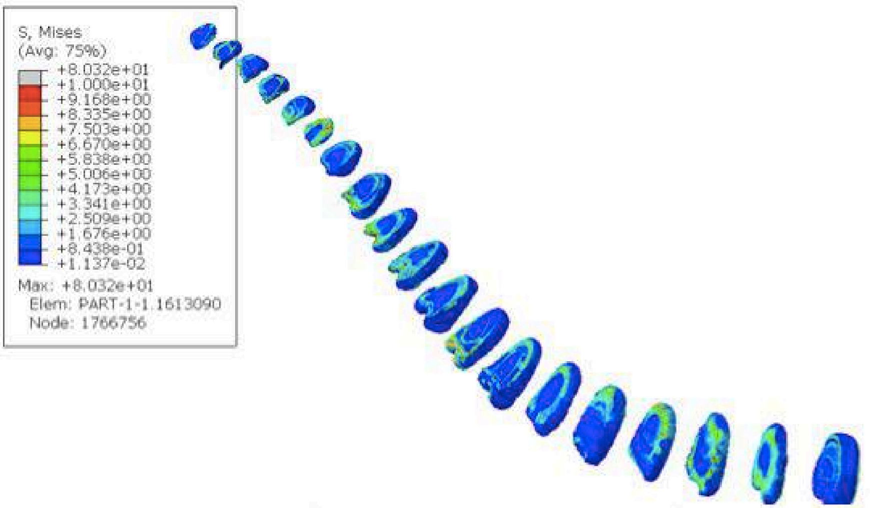

Figure 11. Stress contours on the Spinal Disk

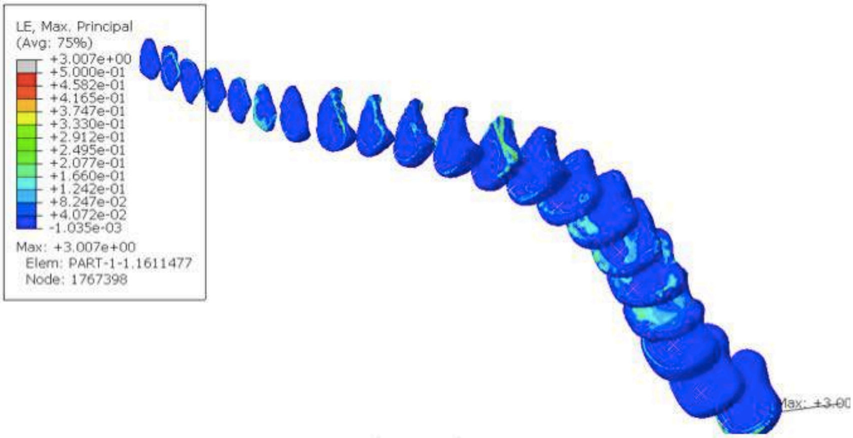

Figure 12. Strain Contours on the Disks

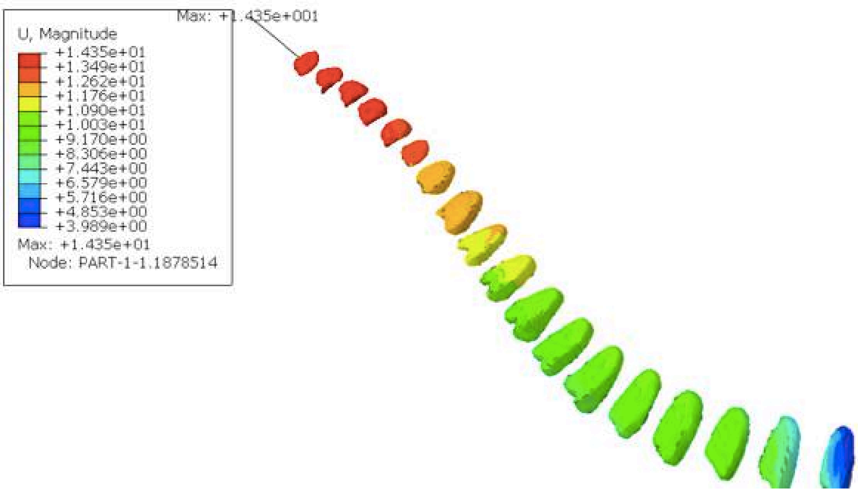

Figure 13. Displacement Contours of the Disks

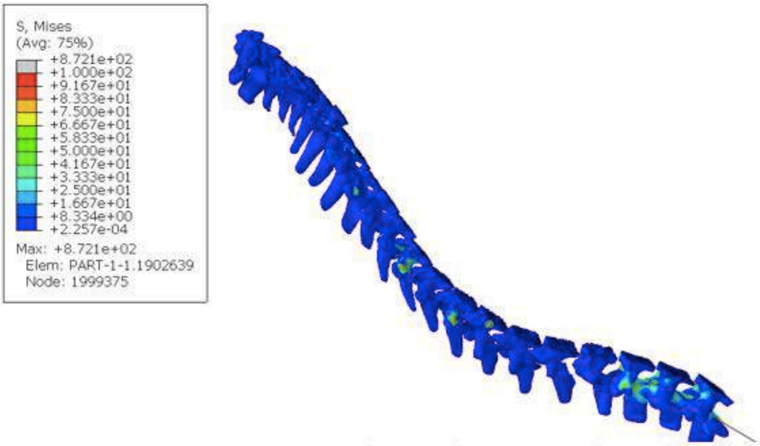

Figure 14. Stress Contours of the Spinal Bone

Figure 15. Strain Contours of the Spinal Bone

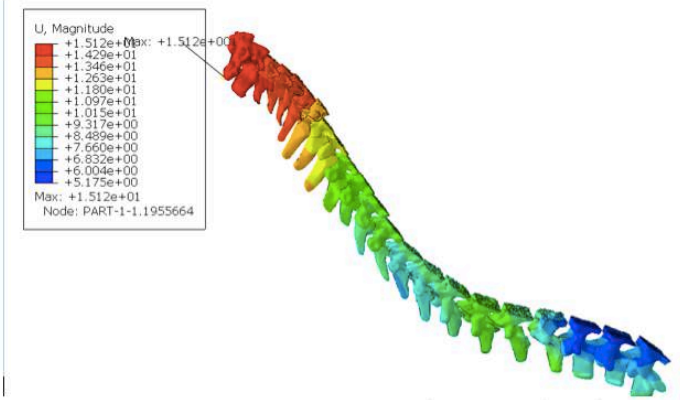

Figure 15. Displacement Contours of the Spinal Bone

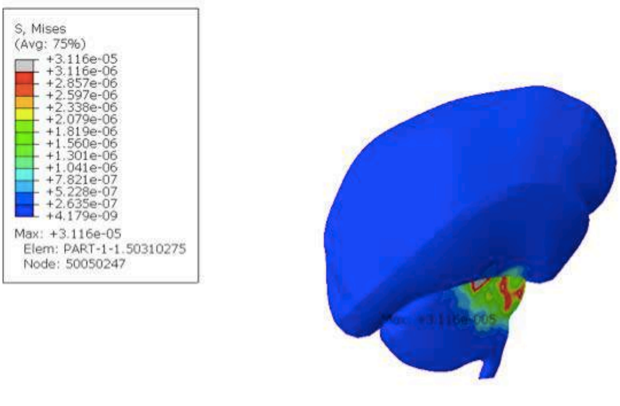

Figure 16. Stress Contours of the Brain

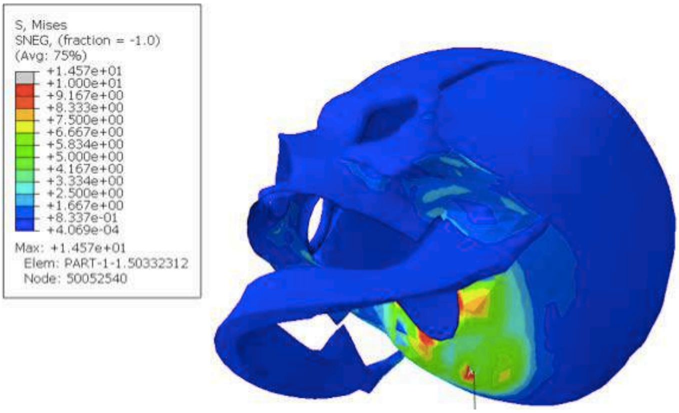

Figure 17. Stress Contours of the Head

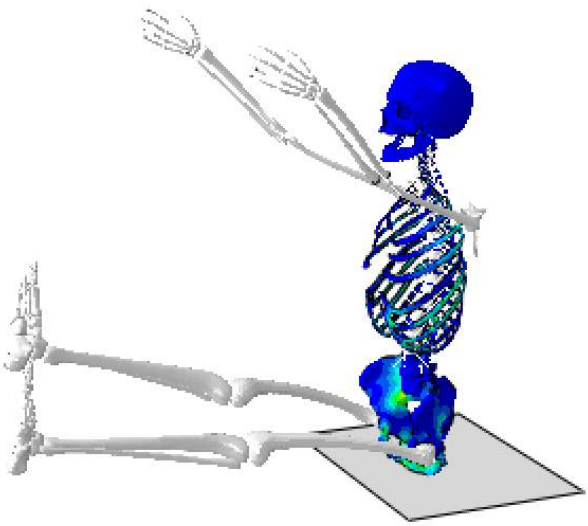

Figure 18. Stress Contours of the Whole Model

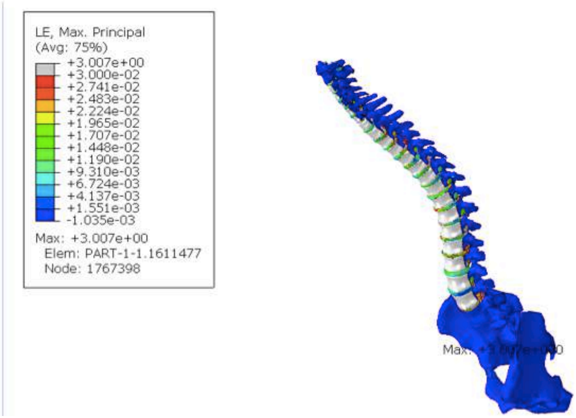

Figure 19. Strain Contours of the Whole Spine

4. Conclusion

It is feasible to analyze the Human Spine and Axial Skeletal System Under Dynamic Loads using FEA. This allows the determination of stresses and deformations for a number of different cases. Having the entire skeleton modeled is important as more details of the muscles get added in, so that more detailed analysis related to impact, can be carried out. While the model is rather complex, it is designed to be very computationally effective with minimum element generation.

There are close to 1 million nodes and 1.5 million elements, but the system has no trouble running on a laptop with 3 CPUs within a few hours to obtain a few milliseconds on data during the impact.

5. Future Work

The current model is skeleton only. So the result is far from meeting the realistic situation. In the future, we intend to add more human parts, like muscle, fat, viscera, etc.

With those parts added, the result would be more accurate than it is now. In addition, one can use this model to test various sports protective equipment or impact from falls or accidents.

6. References

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