AC 2011-2785: APPLICATION OF PARAMETRIC SOLID MODELING FOR ORTHOPEDIC STUDIES OF THE HUMAN SPINE

Jorge Rodriguez, Western Michigan University

Jorge Rodriguez is an Associate Professor in the Department of Industrial and Manufacturing Engineering, and Co-Director of the Center for Integrated Design (CID) at Western Michigan University. He received his Ph.D. in Mechanical Engineering from University of Wisconsin-Madison, received an M.B.A. from Rutgers University in Piscataway, NJ., and a B.S.E. in Mechanical and Electrical Engineering from ITESM - Monterrey Campus in Monterrey, Mexico. Dr. Rodriguez teaches courses in Computer-Aided Design and Manufacturing, Mechanical Design, PDM/PLM, and Biomechanics and Finite Element Analysis. His research is in the field of computational analysis/optimization and educational computer-based tools. He has published one book on optimization, as well as more than 100 papers, with many presentations at national and international forums.

Alamgir A. Choudhury, Western Michigan University

Alamgir A. Choudhury is an Associate Professor of industrial and manufacturing engineering at Western Michigan University, Kalamazoo, Michigan. His MS and PhD are from NMSU (Las Cruces) and BS in mechanical engineering from BUET (Dhaka). His interest includes computer applications in curriculum, MCAE, mechanics, instrumentation & control, and fluid power. He is also a Registered Professional Engineer in the State of Ohio and affiliated with ASME, ASEE, SME and TAP.

Brian Dragone

Application of Parametric Solid Modeling for Orthopedic Studies of the Human Spine

Abstract

Nowadays it is very important that technical people make use and apply available technologies and methodologies to their field of work. In the engineering field there are many computer-based tools that can have a significant positive impact on the manner that several processes and procedures are currently performed, thus making them more efficient and effective. And as educators, it is important to expose students to these technologies, and it is important to motivate their use during their time on campus.

One such technology in the area of Computer-Aided Engineering (CAE) is parametric solid modeling, and one such field would be the field of biomechanics. Parametric solid modeling was initially implemented in a commercial CAD software more than 25 years ago, and right from the start it was identified as a technique that – properly applied – would result in a positive impact in various phases of the engineering design process. Biomechanics as well can be considered a relatively new field in engineering, dealing with the application of engineering mechanics to study anatomical and functional aspects of biological systems. In the biomechanics field we have spine biomechanics and orthopedics, which deal with studying musculoskeletal systems. Students were exposed to these two areas, parametric solid modeling and biomechanics, in the context of a Design Senior Project. One of the most critical problems that doctors and researchers encounter is the lack of effective tools to study, in this case, the human spine. The typical approach is to perform studies with cadaver spines, or with some highly-regulated in-vivo studies on animals. Both alternatives have benefits but they have many limitations as well, thus the need for other tools that will help in their studies.

The objective of this project was to create a fully parametric three-dimensional model of the human spine; with fully parametric implying that every defining dimension of the model can be adjusted at any point throughout creation, or even once the model has been generated. The intention is to be able to represent and analyze various orthopedic conditions of the human spine, such as scoliosis. The senior design team faced many challenges, as with any new area of study, but at the end they had a very rewarding experience that has nicely complemented their college education. This project has particular significance because of the completeness of computer-based technologies utilized; programming and visualization tools were applied to complement the tools offered by CAD software, in order to have usable techniques. Technically, this project is one step towards the creation of a virtual environment where implants can be tested, and surgical procedures and instruments can be probed, and even customizing them for the case at hand. Pedagogically, although very challenging for the students involved, this project was an excellent way to showcase the applicability of engineering concepts and techniques to other fields.

Background

Within the medical community new technology is constantly being sought out to provide more efficient and less invasive methods of treatment and surgery. One such condition that would benefit from these technologies is scoliosis. Invasive and/or destructive testing cannot be applied to analyze this condition as it would be obviously harmful to human subjects and, therefore, illegal and unethical. Given our engineering background, it was imperative that we understand the fundamental anatomy of the human spine, and the pathological terminology associated with the orthopedic conditions, which allowed us to recognize the critical aspects so that we may better implement our design methodology.

General Anatomy. The human spine consists of thirty-three individual vertebrae mainly connected with intervertebral discs and ligaments. The main function of the spine is weight bearing and protection of the spinal cord. The spine is separated into several regions called the cervical, thoracic, lumber, and pelvic. The cervical region is made up of the vertebrae directly below the skull. The vertebrae are labeled from C1 to C7 with C1 being classified as the atlas signifying the topmost vertebrae. The thoracic region contains twelve vertebrae (T1-T12) while the lumbar region consists of five vertebrae (L1-L5). The body, or anterior segment, of a vertebra is cylindrical and attaches to the intervertebral discs in order to allow the spine to move. The vertebral arch is formed by the laminae and pedicles, which, in turn, form the vertebral foramen. The foramen protects and encloses the spinal cord. (National Scoliosis Foundation, 2009)

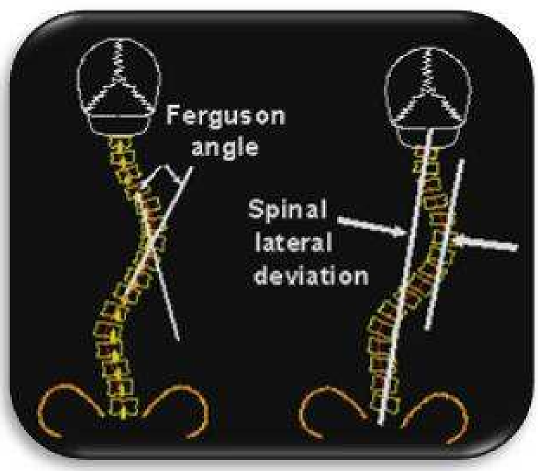

Figure 1. Schematic representation of spine scoliosis.

Scoliosis. It is an affliction in which a person's spine contains abnormal curvature (greater than 10 degrees) and is typically characterized as congenital or idiopathic, depending on when the symptoms first arrive. Congenital scoliosis develops prior to birth and is usually genetic in nature while idiopathic scoliosis develops spontaneously with no known cause, occurring at any age. When examining a coronal (front-view) x-ray the direction in which the curvature takes place further aids in the identification of the type of scoliosis. Curvature to the right is classified as dextroscoliosis and curvature to the left is classified as levoscoliosis (Figure 1). Rotation of the spine can also occur during both types and is classified as rotoscoliosis. (Eck, 2009).

Examining the symptoms and diagnostic procedure of scoliosis is an important aspect in this project because it aids in defining the parameterization of critical features in solid models. The most common form of scoliosis is adolescent idiopathic scoliosis (AIS) and is usually discerned during physical examination in which the patient is asked to bend forward from the waist (Adams bend test). The doctor then searches for any asymmetry in the patient's back. The most common and obvious symptom of scoliosis is back pain. In severe cases of scoliosis there is significant pressure on the heart and lungs causing shortness of breath and irregular heart rates. The severity of the scoliosis is usually determined by the degree of curvature. For instance, 10 to 19 degrees is low risk and likely will not need any treatment, whereas 20 to 29 degrees is considered moderate risk and may need treatment. Above 29 degrees is considered high risk and will need treatment. (Eck, 2009)

The forms of treatment for scoliosis are dependent on the severity of the condition. The main treatments practiced are observation, bracing, and surgery. Observation is used when the curvature is less than 20 degree. If no change in curvature is detected, no further treatment is required. For curvature of 25-40 degrees, bracing is the typical form of treatment with the objective of preventing increase in curvature by applying pressure to the ribs. Depending on the severity, the brace can be worn for 24 hours or only at night. Surgery is the preferred form of treatment for curvature greater than 40 degrees. Spinal fusion is used to fuse individual vertebra together in order to prevent any further increase in curvature. (Reamy and Slakey, 2001).

Computed Tomography. Medical imaging and visualization require means to gather geometry from the complex features of the human anatomy. Due to the complexity of features in the spine it would seem beneficial to acquire these data from a more precise and accurate means than manual measurements or judging by the naked eye (e.g. Adam's bend test). These are the main reasons for exploring computed tomography (CT) technology. CT is a technology that uses many two dimensional x-rays taken about a central axis to generate high contrast cross sections of the human body. CT scans are generally used to identify any peculiarities within the human body.

3D Slicer Software. It is a software that helps in visualizing and evaluating the data sets produced by the CT machine. 3D Slicer started as a graduate school thesis project, but is now a popular open source software for visualizing medical images. 3DSlicer uses a selected range of gray scale densities that are present in the MRI images to segment parts from the whole in a given sample. It contains multiple different modules for assistance in the creation of solid models. (BWH and 3DSlicer contributors, 2009). Manual image segmentation uses simple drawing tools and threshold capabilities to segment individual slices within the data set. These options give the ability to edit and customize segmentations created with the threshold tool. This proved useful for segmenting CT images into usable label maps that form the foundations for creating a three dimensional model. (Olszewski, nd). Modelmaker is a module used to create 3D surface models from segmented image data, called label maps. Label maps can be the result of automated segmentation or interactive editing. The user can specify the number of smoothing iterations and control the type of smoothing done on the models. Once a model is generated, it can be exported as stereolithography file (.stl), which can be opened in most CAD softwares.

Parametric Modeling. It is the approach followed by most modern solid modelers. One objective of using parametric modeling is to simplify the overall design process when various conditions and scenarios are desired. In a properly parameterized model/assembly, if the user desires to change a dimension all other related dimensions will automatically be adjusted to adapt to the changes. Parametric modeling is achieved through the programming of parameters and relations into the CAD software. In dealing with scoliotic spines, parametric modeling will be greatly helpful in situations when CT data corresponding to a certain scenario cannot be obtained or when the user (e.g., orthopedic surgeon) wishes to examine extreme or rare situations.

Methodology

The project followed the following general steps for its completion:

- Segment CT scans – CT scans of the spine were segmented into label maps defining pertinent anatomical features using 3DSlicer.
- Create models – 3D solid models and .stl files were created from the label maps.
- Place scoliosis reference geometry – Geometric standards for describing scoliotic conditions were deduced from surface models into the CAE software.
- Assemble individual vertebrae – The vertebrae were assembled in CAD software according to their initial normal positions.
- Parameterize to simulate scoliosis – Use parametric solid modeling to establish relationships between dimensions and corresponding geometrical features.

The CT scans were acquired for the National Library of Medicine's Visible Human Project which is for educational use only. 3DSlicer is on open-source software initially developed as a Harvard Medical School graduate project. Educational licenses of Pro/Engineer and ATOS were also used throughout the project.

Results

The Segmentation process consisted of using paint and pen tools within 3DSlicer to specify the desired anatomical features to be used in model creation. A threshold tool is also available within 3DSlicer to specify limits and accurate selection. By segmenting the CT images for each desired anatomical feature a label map is created. The label map has a unique number and color (label) for each anatomical feature as assigned by the user. A demonstration is provided in Figure 2.

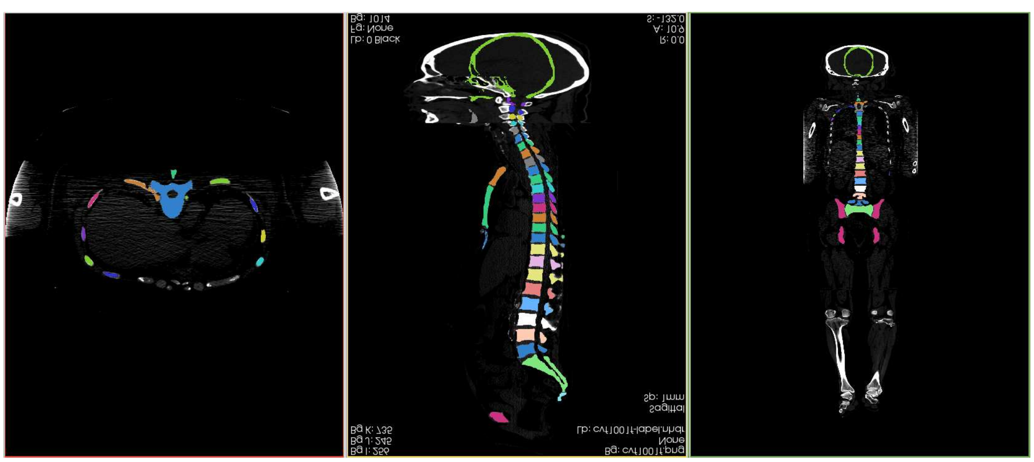

Figure 2. Completed label map shown in three orthogonal views (axial, sagittal, coronal)

After the challenging, and sometimes painful, learning process for 3DSlicer, a problem that was encountered several times during the segmentation process was the scaling of the CT scans. Specifically, the skull region was distorted through enlargement of consecutive scans. This problem was alleviated by the measuring of analogous features in two consecutive slices from which a scaling factor was derived. The measurements can be made in most image editing programs (i.e. GIMP).

When the label map was completed for all of the desired geometry, models were created. This was done with 3DSlicer. The software is able to interpret the information assigned to the label map by the user and interpolate it to make three dimensional surface models. More than 20 iterations, on average, were applied within the Modelmaker module to each vertebra as it was created. This amount of smoothing was selected because it is expected to hold the most fidelity to the anatomy while also achieving the desired realistic likeness. The models were placed into a hierarchy based on their anatomical region, and nomenclature was assigned based on standard convention for vertebrae (e.g., T2, L3). Other models that were created include the pelvis, rib cage, sternum, cranium, and mandible (Figure 3).

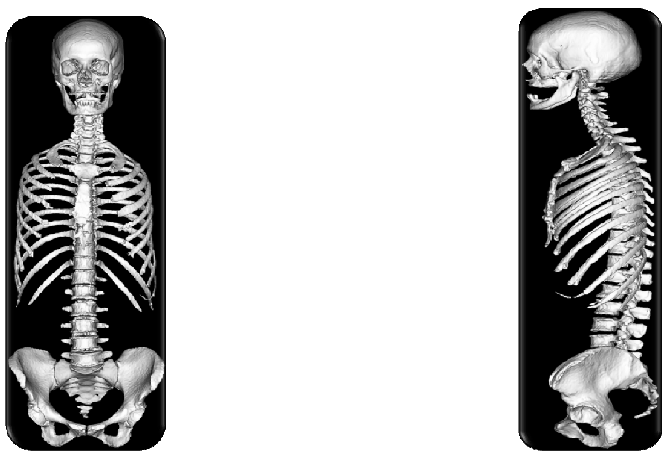

Figure 3: Anterior Coronal and Left Sagittal views of models created in 3DSlicer.

A vertebral centroid is "the point halfway between the centers of the two endplates of a vertebra". These centroids are used as local coordinate systems for each individual vertebra. A vertebral body line is "the 3-D curved line that passes through the centroids of the vertebral bodies". Spinal lateral deviation is used in addition to the end and apical vertebrae to define the curvature of the spinal deformity. It is the distance of the most laterally deviated vertebra from the spinal axis (Figure 1). (Stokes, 1994). Vertebral endplates are the top and bottom portions of the vertebral bodies that interface with the intervertebral discs (Vertebral Endplates, 2010). In order to obtain this data, the .stl file was imported into the ATOS software, where appropriate points were selected and best-fit planes were created to represent the endplates (Figure 4). For consistency, it was found that when following the provided definition for vertebral endplates a value of less than 0.25 was acceptable when dividing the standard deviation of the points by the total range.

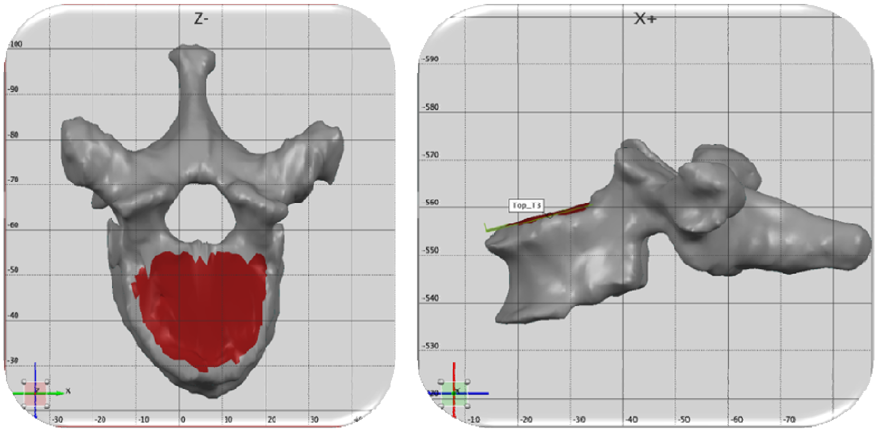

Figure 4: View of vertebra's superior endplate and point selection.

For parameterization and constraining of the spine assembly the sequence first consisted of patterning the vertebra centroid locations as datum points using Pro/Engineer's pattern table function. Next, a spline was created through each datum point representing the natural curve developed in the human spine. Then, based on the desired degree of deformity that is being modeled, a graph curve is created to define the curvature of the hypothetical severity. This also allowed for the specification of the superior and inferior vertebra endplates, as well as, the apical vertebra and its lateral deviation. Next, each vertebra was assembled, with a constraint applied to its centroid and its corresponding datum point. The central axis of each vertebra was then constrained tangentially to the 3D curve, for proper orientation. Once fully assembled, the assembly was programmed to specify translation and rotation of vertebrae in relation to user inputted parameters. Pro/Program was used to setup a user input dialog box prompting for the desired superior end vertebra, inferior end vertebra, apical vertebra and lateral deviation, and the direction of curvature. Finally, a Ferguson Angle was derived as a reference within the curvature graph. Figure 5 shows a parametric model for a Ferguson Angle of 41.85^{o}.

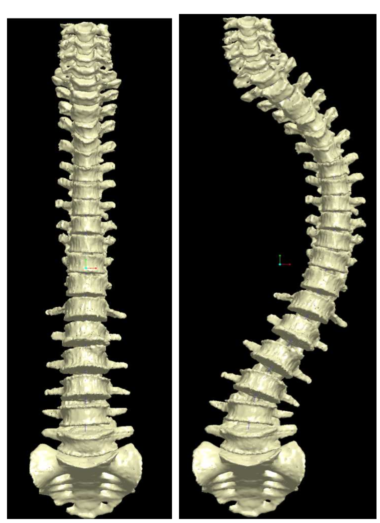

Figure 5: Parameterized model with Ferguson angle of 41.85°

Conclusions

Solid models were achieved by utilizing a visualization and image computing software program for the specific purpose of CT segmentation. The segmentation process distinguished between the gray scale densities of different tissues of the human body. This served as the initial step for a three-dimensional reconstruction based entirely on the provided CT scan data. In addition, computer-aided design software was used to generate a parametric assembly of the models. The parameterization produced a model of hypothetical circumstances without having to attain additional sets of MRI data. These models certainly will aid in the development of new treatments through the application of analysis and simulation tools. Supplying medical and engineering professionals with a usable parametric solid model of a scoliotic spine will allow them to advance treatment techniques in the future by evaluating hypothetical situations. Parametric models will be beneficial to medical professionals and engineers because this will allow for more rapid analysis and solutions which ultimately is beneficial to the patient.

This was a very challenging and rewarding senior design project for the students in an Engineering Design Technology program. This project really hits the Multidisciplinary aspect that is expected in a capstone project. Students were required to go beyond the subjects and tools that are learned in their coursework, and learn about spine anatomy, biomechanics, 3DSlicer, and integrating several CAE tools into one common project. Great feedback was received from faculty and industry people, and the students get highly satisfied with the experience at the end. This project is a showcase currently used in our recruiting efforts.

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