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Development of 3D Kinematic Model of the Spine for Idiopathic Scoliosis Simulation

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ABSTRACT

This paper presents a methodology for developing kinematic model of the human scoliosis simulator using 3D models of spinal vertebrae reconstructed from point clouds. The main objectives of the work are (i) to reduce the number of spinal radiographs required for measuring idiopathic spinal deformities, the most common spine deformity (more than 80% of cases) at adolescents and (ii) improve the visualization and measurement for better treatment planning. The reconstructed 3D model is parameterized and used as a reference model for creating patient-specific anatomical models based on dimensions extracted from radiographic images (Cobb angle and dislocation of vertebrae). The methodology has been implemented and demonstrated with a case study.

Keywords: point clouds, kinematic model of spine, 3D idiopathic scoliosis simulator.
DOI: 10.3722/cadaps.2010.153-161

1 INTRODUCTION

Idiopathic spinal deformities are the most common spine deformities (more than 80% of cases) at adolescents and typically progresses during the adolescent growth spurt [1]. The risk of curvature progression is increased during puberty, when the growth rate of the body is the fastest. Scoliosis with significant curvature of the spine needs immediate treatment as it more likely to progress. The traditional way of identifying the spinal deformity is measuring the angles of scoliosis curves directly on the X-ray films [4,5]. Three dimensional knowledge of the bony anatomy is vital in visualizing true representation of anatomic structures and in the therapeutic and prognostic aspects (accurate measurement of irregularities and curvature in the complex spinal structures). The pre-operative reconstruction of 3D anatomical models can be performed through the use of direct 3D imaging modalities such as CT/MR Images. However the use of such imaging is restricted to a minority of complex procedures due to constraints placed by cost, availability and risks posed by unwarranted detailed imaging (such as radiation risk). Thus an alternative to direct 3D imaging must be developed to augment procedures that currently rely on pure 2D radiographs. Developing a three-dimensional scoliosis simulator can significantly reduce exposure of radiations as well as gaining 3D visualization, monitoring and therapy individualization. The developed model can also be used for downstream applications like designing braces, surgery guidance, etc.

This paper describes a computer-aided methodology for creating 3D model of the human spine from point clouds, Digital Mock-UP (DMU) model of normal spine for in-vitro measurement of range-of-motion, and simulation of scoliosis model based on radiographic images of patient.

2 3D RECONSTRUCTION OF THE HUMAN SPINE

A cast model of human cadaveric spine was scanned using ATOS IIe optical high-end 3D Digitizer (GOM GMBH, Germany). The digitizer works on the principle of spatial triangulation and generates a cloud of points on object’s surface. The 3D model of the spine was generated from the cloud of points by fitting NURBS surfaces using Geomagic Studio (Geomagic Inc., USA) software system. The surface data of the spinal vertebrae was imported into the PLM system CATIA (Dassault Systems, France) for kinematic simulation. Figure 1 details the workflow of digitizing and generating 3D model of spine.

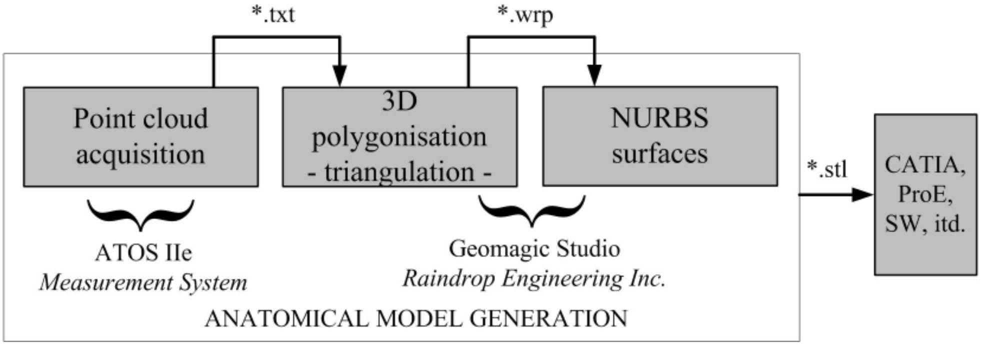


Fig. 1: 3D reconstruction of the spinal vertebrae from point clouds to volume models.

Optical reference markers were placed on major landmarks on the spine model to ensure the registration and orientation of each vertebra. The ATOS IIe system projected fringe patterns (high light power mode) on the model. High light power mode was used to reduce the effect on ambient conditions on scanning. Photosensitive Charge Coupled Device (CCD) cameras detect the light reflected from the scanned object under certain angle. Two cameras recorded the point clouds of surface of the object and dedicated software program computed high-precision 3D coordinates (range of 4 million points per measurement). Measurement characteristics: points: 1,400,000, area: 175 x 140 - 2000 x 1600 mm², and point spacing: 0.12 - 1.4 mm. Figure 2 shows a step of acquisition of point clouds. The same procedure is repeated for each vertebra of the total spine. The complete 3D data set is exported for further processing.

Figure 3 gives the steps followed in reconstructing the most complex element of the spinal column (sacrum and coccyx vertebrae) from point clouds using Geomagic Studio (Geomagic Inc., USA) software program to describe the methodology. Processing point cloud includes optimization and reduction of the number of points, and that without losing representativeness [9]. Points of discontinuity (due to vibration during scanning or inadequately prepared surface of the scanned object) are removed by simple operations. Inaccessibility of some areas during scanning and light reflection from the polished surface leads to loss of the group points. The polygon stage provides detection, removal, reparation and relaxation set of triangles and determines the level of smoothness reconstructed polygonal surface. Decimation is done to reduce a total number of triangles without losing consistency and topology. Key step in generating of NURBS surfaces is the decomposition polygonal models in set of patches. Grid of Bézier splines is actually a set of curves and its density depends on the quality of reconstructed surface models. Detection of contour lines that represent the largest curvature causes the decentralization of polygonal surfaces in several areas. After grid fitting, we created NURBS surfaces and exported STL model of each vertebrae. We reconstructed and converted into 3D volume models all groups of vertebrae (sacral, lumbar, thoracal and cervical). Tangential and global continuity (G1) reconstructed models are also satisfied. By exporting the surface model in STL file, the process of 3D reconstruction is completed. In processing of the point clouds obtained by optical method (a total of 509,663) the number of points is reduced to 373,548, and generated 747,114 triangles. After processing, the total number of triangles is 701,517 and 2473 patches.

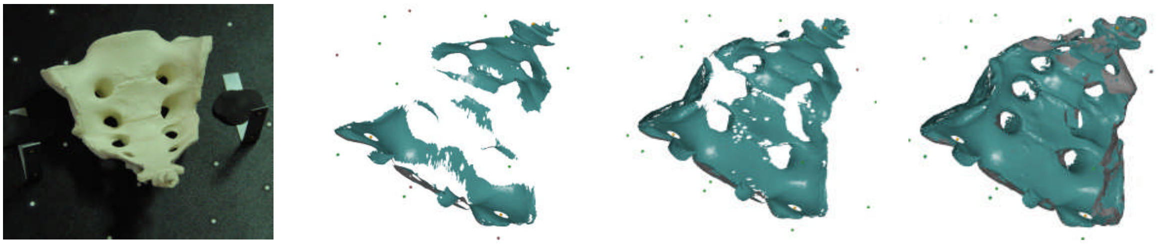
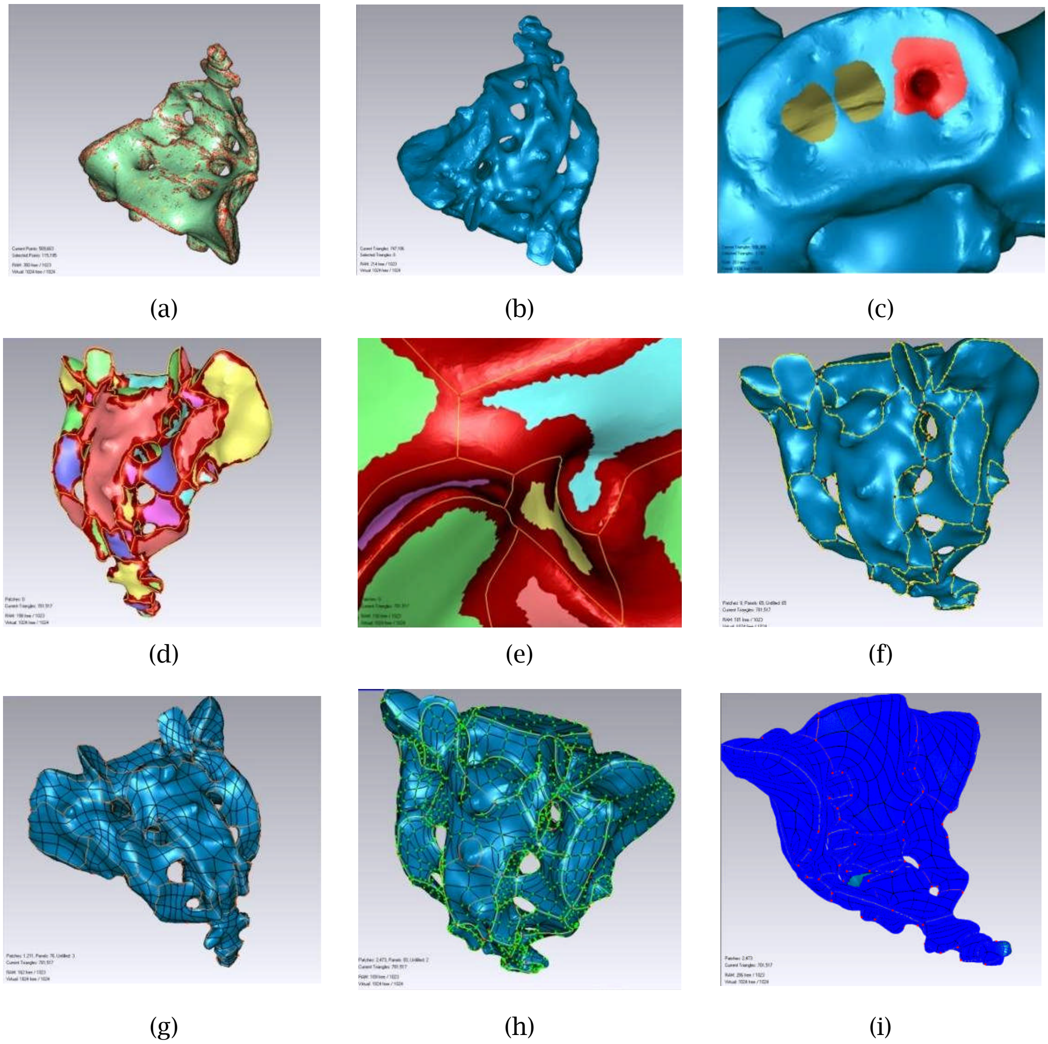


Fig. 2: Point clouds acquisition on ATOS IIe: (a) preparing of phisicaly model, (b) point generation.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig.3: Illustration of point cloud reconstruction in Geomagic Studio: (a) point clouds, (b) poligonal model, (c) triangle healing, (d,e) contour detection, (f) contour optimization, (g) patches detection, (h) patches optimization, (i) surface grid fitting.

3 KINEMATIC MODEL OF THE HUMAN SPINE

The exported STL data of the 3D vertebra models were imported into CATIA V5R14 (Dassault Systems, France), a PLM software program. The total vertebral column (spine model) was created by assembling individual vertebrae based on the landmarks (reference markers). Anatomic and geometric coordinate systems (ACS and GCS) were established and referenced to generate the kinematics model of the spine (parametric based) for simulating spinal deformities. The local *z1* axis of vertebrae passes through the center of the upper and lower endplates of a vertebral body. Local *y1* axis is parallel to the line joining the centers of the left and right pedicles. The local *x1* axis is normal on y1 and z1 axes and completes a normal right-handed coordinate system (Fig. 4). The upright position of the human spine is bent in the shape of a double letter "S" as shown in figure 5.

To generate the parametric model, the total spine was visualized as a geometric entity rather than an anatomical model. Spinal column has a series of segments, which are called dynamic vertebral segments (DVS). There are 7 Vertebrae cervicales, 12 Vertebrae thoracales, 5 Vertebrae lumbales, 5 Vertebrae sacrales, and 4-5 Vertebrae coccygeales. Spinal vertebrae form the spinal canal in which the spinal cord lies. Between vertebrae bodies are discus, which make up ¼ of the height of the spinal column (height of the discus between cervical vertebrae is about 3 mm, thoracales 5 mm, and lumbales 9 mm).

Vertebrae are solid bone structures and considered as rigid bodies, whereas the total spine is flexible (assembly of vertebrae). Model of vertebrae are connected by spherical joints and movement of the spinal column is the sum of rotations between inter-vertebral joints. Spine can be deformed in complex ways because it is a collection of multiple rigid bodies linked together by soft tissues such as joint capsules, ligaments, intervertebral discs, and muscles. Angular deformations of the spinal segments are different from normal range of motion (Table 1) and may result along one or both of the axially oriented axes following the application of a bending moment. Such abnormal rotations cause spinal kyphosis, lordosis, scoliosis or a combination of these deformities.

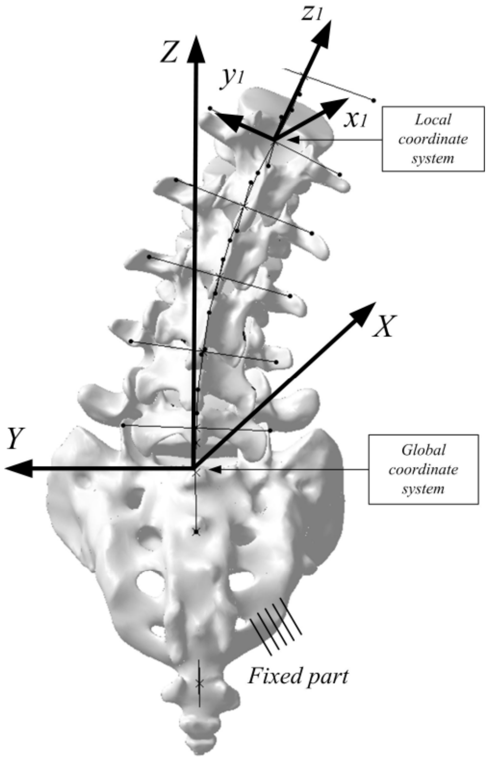


Fig. 4: Axis systems: global spinal axis and local vertebrae axis.

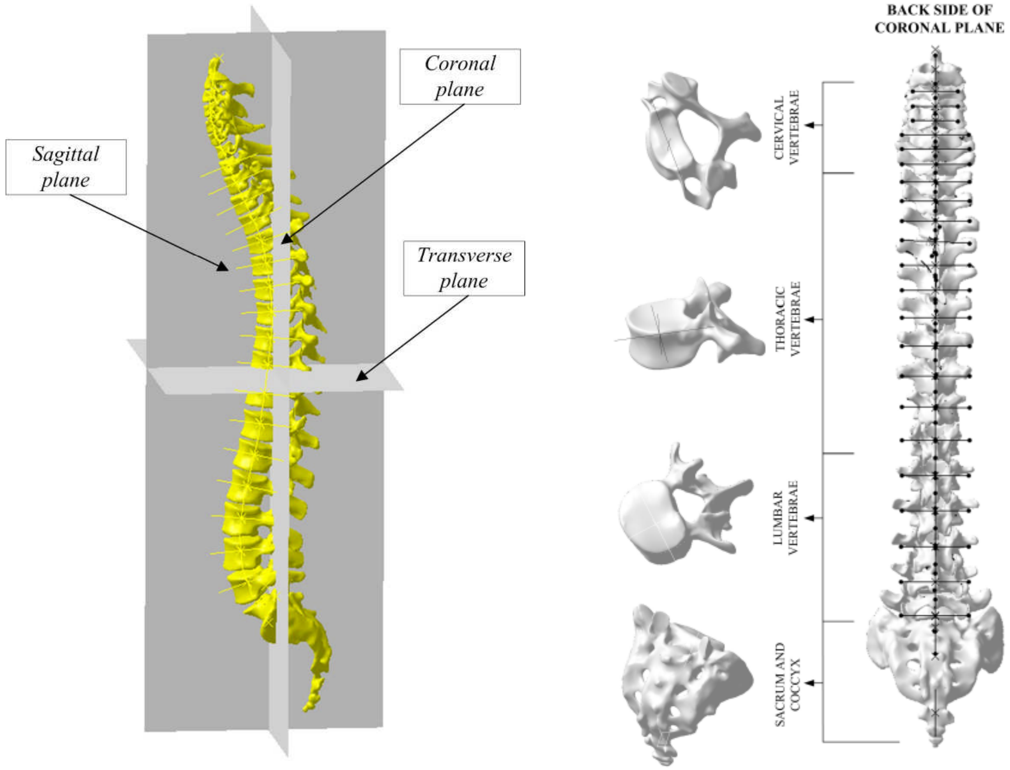


Fig. 5: Generic model of human spine: (a) planes – spatial view (b) characteristic regions and model of veretbrae – anterior view.

Level	**Flexion/ extension**	**Right/left bending**	**Right/left rotation**
Cervical spine	40°/75°	35°/35°	45°/45°
Thoracic and lumbar spine	105°/60°	20°/20°	35°/35°
Lumbar spine	60°/35°	20°/20°	5°/5°
Total	**110°/140°**	**75°/75°**	**90°/90°**

Tab. 1: Total movement of the normal spine.

The vertebral body-line can be visualized in a three characteristic planes: coronal, sagittal, transverse for defining deformities. In front view, projected in coronal plane (which divide the body into front and rear), spine has no curve (ideal condition). If there is a lateral curvature then such a deformation is called scoliosis. Geometrically, scoliosis can be defined as three-dimensional rotation of torso (includes the side distortion of the spine). Therefore, the lumbar section performed mainly flexion and extension movements and a very small movement of rotation. All of these deformities could be simulated by developed 3D model.

The King and Lenke classification has continued to be utilized despite the increasing acceptance of the need to consider scoliosis as a 3D deformity when considering operative intervention. New Lenke classification of adolescent idiopathic scoliosis is much more reliable than the King system [3].

As a result of the three rotations of each vertebra, spine can bend around three fixed axis X, Y, Z: flexion/extension, lateral bending and axial rotation. For global and spinal axis of patients we placed origin at the center of the superior plate of fixed sacrum model [6, 8,10].

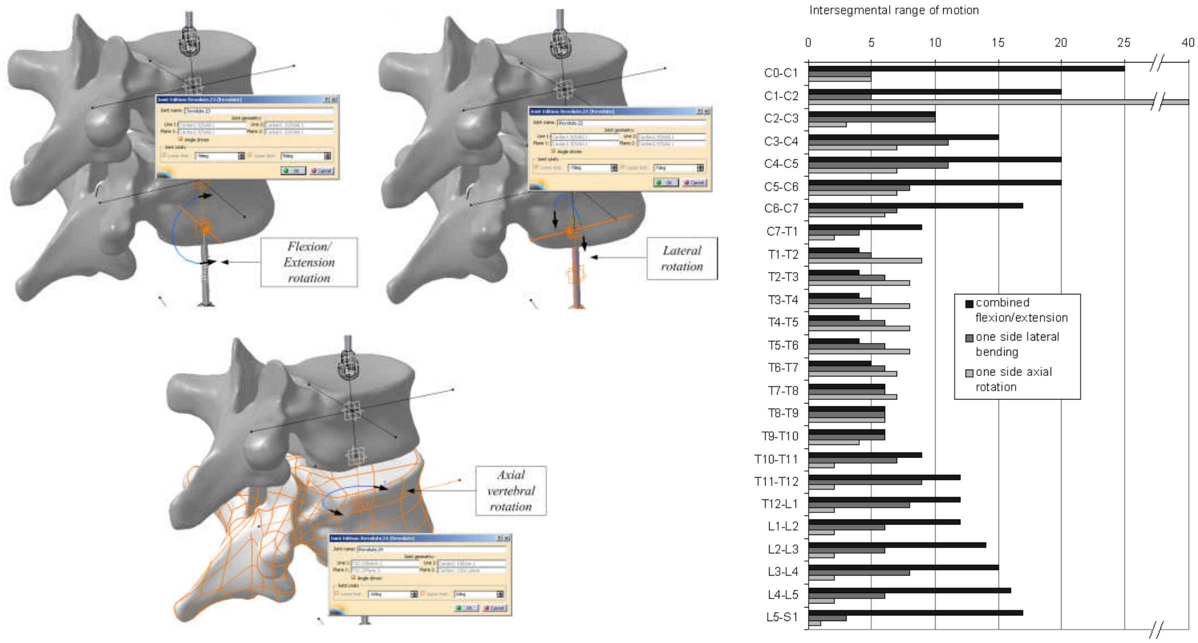


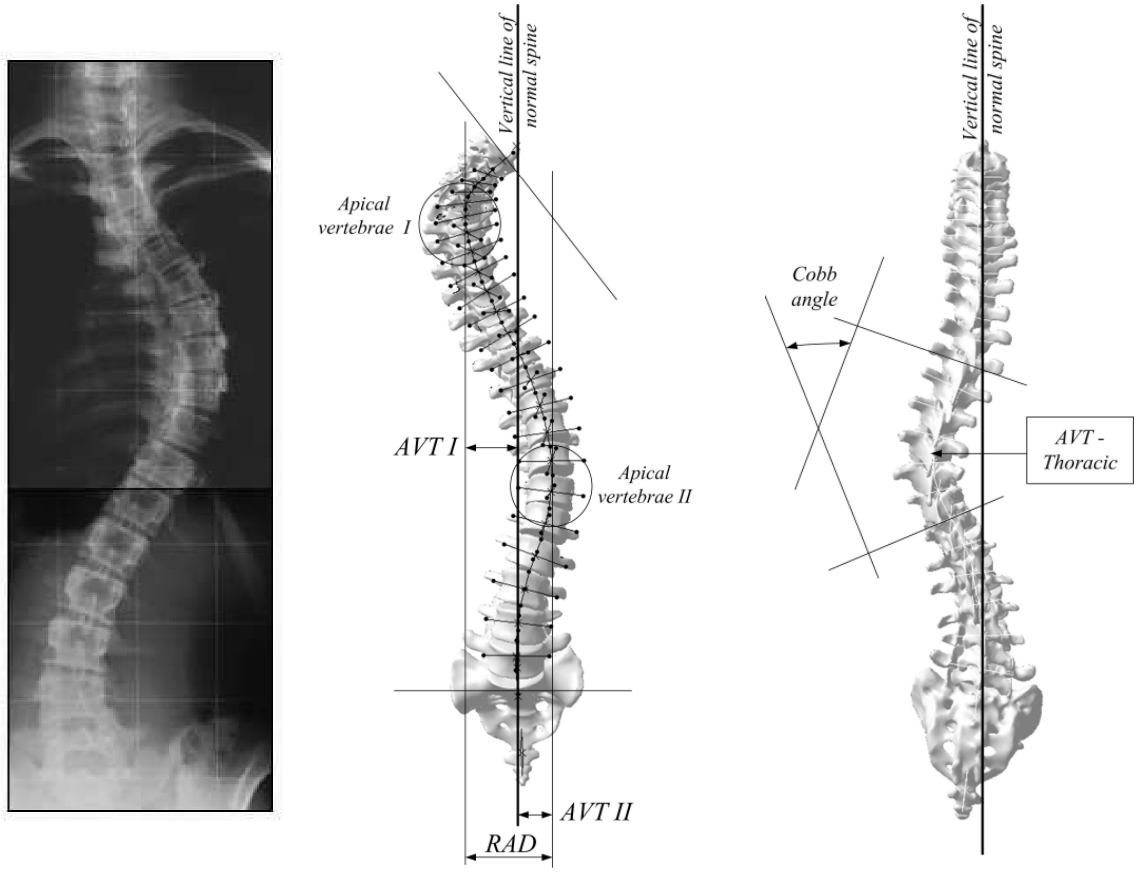
Fig. 6: Three relative rotations of vertebral segments for normal spine.

4 APPLICATION OF KINEMATIC MODEL TO IDIOPATHIC SCOLIOSIS SIMULTIONS

3D reconstruction of the spinal bone structures facilitates visualization of the 3D spine deformity. This is of primary importance considering the complex 3D deformation involving lateral deviation of the spine, vertebral rotation, modification of the sagittal profile and global geometrical torsion [2].

Developed 3D model provides the 3D visualization of idiopathic scoliosis based on parameters of dislocations of apical vertebrae from vertical line and Cobb's angles derived from x-ray images (AVT – Apical vertebrae translation, RAD – Relative apical dislocation) (Fig. 7). This interactive tools is a part of our information system ScolioMedIS and is curently being testing in a clinical randomized trial within The Physical Medicine and Rehabilitation Center Kragujevac to evaluate its effectiveness compared to traditional methods of spinal treatements. Parametric 3D model of the spine allows for simulation of scoliosis using initial digital radiographs (Fig. 8).

The approach assumes to select typical clinical landmarks of the deformation, e.g. translation (dislocation) of apical vertebra, and enter other relevant body parameters, upon which digital mock-up transforms an "ideal" spinal shape to the deformed one. Calculation of Cobb angle performs automatically, and King's or Lenke classification [3] can optionally be derived. In the case of idiopathic scoliosis, for instance, the model provides radiation-free monitoring after each stage of prescribed therapeutic procedure and exercises using clinical measurement of external body parameters. Archiving of patients' records is easy and helps for individualization of therapeutic actions.



(a) (b) (c)

Fig. 7: Visualisation of the spine deformity : (a) Primary radiography image, (b) Parameters of translation and dislocation – anterior view, (c) Cobb angle measurement – posterior view.

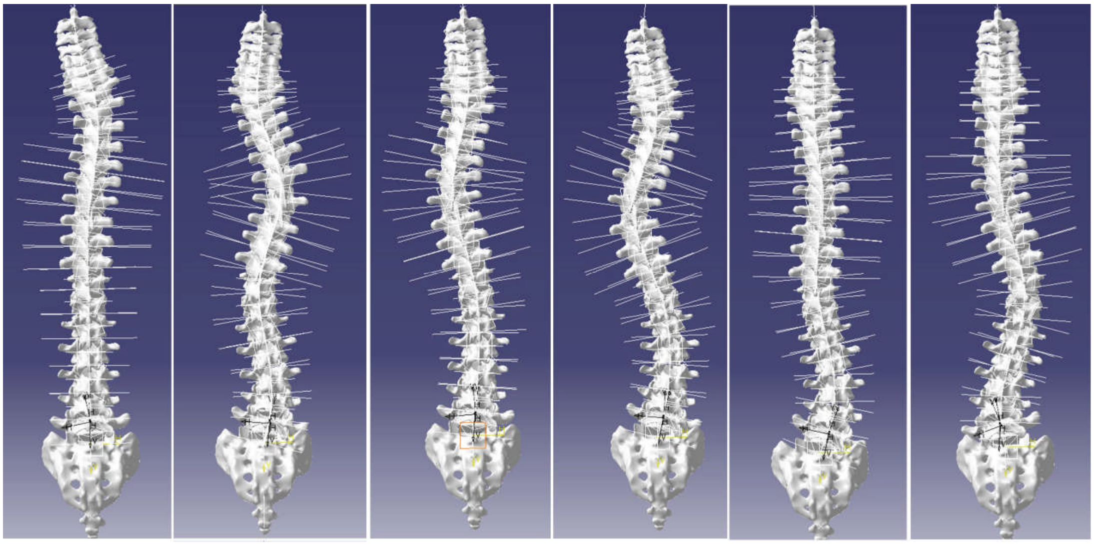


Fig. 8: Parametric 3D simulation of scoliosis.

The spacial curve obtained from the control points of each vertebra of normal or deformed spine must be smooth. In a normal spine, the curve in the sagittal plane has a „S“ shape, with a concave region and other convex one with a point of inflexion [5]. The two invariant parameters in the 3D curve are local or global curvature and torsion. PLM system CATIA allows to analyse these parameters (Fig. 9).

In this aspect, this work contributes a developement of a 3D classifier that uses the information of 3D geometric invariants from the current classifiers based on x-ray images.

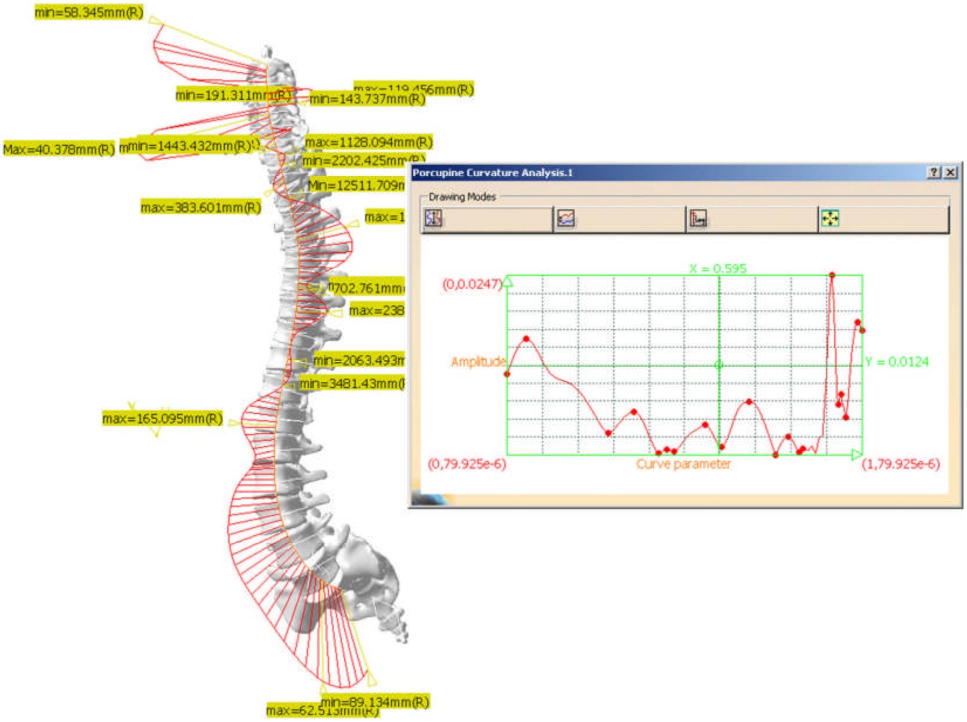


Fig. 9: Curvature of the spinal curve for a patient with thoracolumbar scoliosis.

5 CONCLUSIONS

We have described the methodology of development of three-dimensional kinematic model of the spine for diagnosis, visualization and treatment of idiopathic scoliosis deformity. This has been achieved by the combined use of digitization, surface fitting and geometric modeling techniques and tools readily available and used for engineering applications. The work demonstrated that the use of critical parameters extracted from a couple of radiographic images of the patient to individualize the 3D model for patient-specific treatment planning. Utilization of 3D parametric kinematic model of the spine and scoliosis simulator enable clinicians and patients to substantially reduce exposure of X-rays, simultaneously gaining three-dimensional visualization, enabling patient-specific monitoring, therapy, braces, and implants. The limitations of the proposed methodology is that it focuses on kinematic parameterization for scoliosis than anatomical parameterization. Incorporating active shape models (manual or automated) along with the geometric reasoning algorithms to generate patient-specific 3D anatomical models from X-ray images would improve the accuracy of the models and provide rich quantitative information. The integrated methodology has been demonstrated for a case study. Further testing of the methodology using a larger number of cases can be taken up to tune-up and optimize the algorithms for practical applications.

ACKNOWLEDGEMENTS

The work is a part of ongoing research on “Development of Scoliosis simulator for diagnosis and treatment.” in Center for Integrated Product and Process Development and Intelligent Systems at Faculty of Mechanical Engineering, Kragujevac in collaboration with Faculty of Medicine Kragujevac. The research is supported by the Ministry of Science and Technology, Republic of Serbia under the grant of "Ontological modeling in bioengineering".

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