Journal of Production Engineering
Vol.18 No.2

JPE (2015) Vol.18 (2) Preliminary Note
Ćuković, S., Devedžić, G., Luković, V., Anwer, N., Zečević Luković, T., Subburaj, K.

3D MODELING OF SPINAL DEFORMITIES SHAPES USING 5TH DEGREE B-SPLINES

Received: 27 September 2015 / Accepted: 20 November 2015

Abstract: *In this article, we present a new methodology to model spinal deformities in patients with idiopathic scoliosis. This approach uses a5th degree B-spline to characterize the deformities by taking central spinal line as a reference for positioning and orienting vertebrae.Generic 3D model of the spine and 3D optical scans of dorsal surfaces were used to generate the control vertices required to generate the central spinal line. B-spline based mathematical representation of central spinal line provides a set of quantitative measures to assess spinal deformities. This methodology was applied on a representative dataset consists 372 adolescent idiopathic scoliosis patients and tested for its effectiveness.*
Key words: *Scoliosis, B-spline Curves, Adolescents, CAD, 3D Spinal Model*

3D modeliranje oblika spinalnih deformiteta primenom b-spline krivih petog stepena. *U radu je predstavljena nova metodologiju u modelovanju deformiteta kičmenog stuba kod pacijenata sa idiopatskom skoliozom. Ovaj pristup koristi B-spline krive petog stepena da se karakterišu deformiteti kičmenog uzimajući centralnu liniju kao referencu za pozicioniranje i orijentaciju vertebrae. Generički 3D model kičme i 3D optičko skeniranje leđne površine su korišćeni za generisanje kontrolnih tačaka potrebnih za generisanje centralne spinalne linije. B-spline na bazi matematičkog predstavljanje centralnog kičmene linije obezbeđuje skup kvantitativnih mera u cilju utvrđivanja kičme deformiteta. Ova metodologija je primenjena na reprezentativnom uzorku koji se sastoji od 372 adolescenata sa idiopatskom skoliozom pacijenta i testiran je za njenu efikasnost.*
Ključne reči: *Scoliosis, B-Spline krive, Adolescenti, CAD, 3D model kičme*

1. INTRODUCTION

Adolescent Idiopathic Scoliosis (AIS) is a spinal deformity that can be characterized by lateral deformities of the dorsal surface and trunk. This deformity causes various health problems for these patients with continuous progression in addition to being unaesthetic, so the secondary lifestyle diseases, like clinical depression and difficulties of doing activities in the workplace also increases. The current clinical standard for diagnosis and monitoring of these patients is based on Cobb's angles, measured using sagittal and frontal radiographic images. Significant technical and procedural advances in non-invasive imaging modalities offer new avenues to diagnose and monitor scoliosis [1]. One of these modalities is 3D optical scan that digitize dorsal surfaces using traditional raster-stereography principle with modern equipment.

In this study, we have used generic 3D model of spine and 3D optical scan to generate central spinal line. To represent an intricate 3D shapes and curves in computer aided design (CAD) environment, we tested various freeform curves including μ-splines, β-splines, nonlinear splines, exponential splines, splines in tension, and B-splines. Although B-spline curves are the most widely used, due to easy handling and computational efficiency [2], we have adopted them for modeling spinal deformities.

1.1 Characteristics of B-splineCurves

This section describes the main characteristics of B-spline curves that are needed to model spinal deformities in patients with AIS. If there are positive integer parameters k and n, where in $k < n+2$, and known knot vector $(t_0 < t_1 < ... < t_n < t_{n+1} < ... < t_{n+k})$, as well as the $n+1$ points of the control polygon: $a_0, a_1, ..., a_n$, then the parametric curve c represented by the function $p(t)$ in formula (1) is B-spline curve, defined on the control knot polygon $a_0, a_1, ..., a_n$ and by the node vector $(t_0, ..., t_{n+k})$. Points denoted as a_i are control points of the control knot polygon, or de Boor's points, $N_{i,j}(t)$ is basic spline function [3]. If the node interval is $[t_i, t_{i+1}]$ and if lengths between corresponding nodes are equal, the node vector is then uniform. B-spline curve created by this property is called uniform B-spline curve (Figure 1). The node vector with non-uniform distribution of nodes defines the non-uniform B-spline (non-uniform B-spline curve). Parameter *n* in (1) represents degree of B-spline curve.

$$p(t) = \sum_{i=0}^{n} N_{i,j}(t) \cdot a_i \text{ for } t \in [t_{k-1}, t_{n+1}], \quad (1)$$

In accordance with mentioned, main characteristics of the B-spline curves are:

- For $t \in [t_l, t_{l+1}]$ applies that segment of B-spline defined on the interval $[t_l, t_{l+1}]$ depends only on the k control points: $a_{l-k+1}, ..., a_l$, and then it can be described as follows:

$$p(t) = \sum_{i=0}^{n} N_{i,j}(t) \cdot a_i = \sum_{i=l-k+1}^{l} N_{i,k}(t) \cdot a_i \qquad (2)$$

-Curve is invariantly associated with the control polygon $a_0, \ldots, a_n$ by affine transformations;

-If B-spline curve is smooth at each subinterval of interval $[t_i, t_{i+1}]$, then B-spline curves are C^{k-2} continuous in points $p(t_i)$.

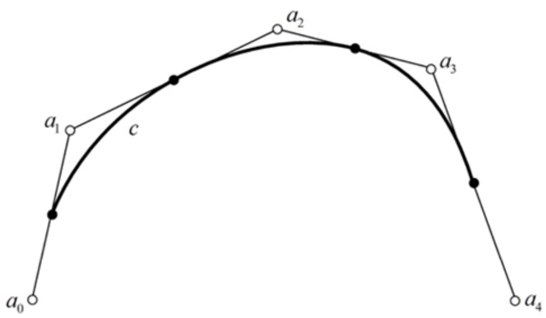


Fig. 1. Uniform B-splinecurve for $n = 4$ and $k = 3$

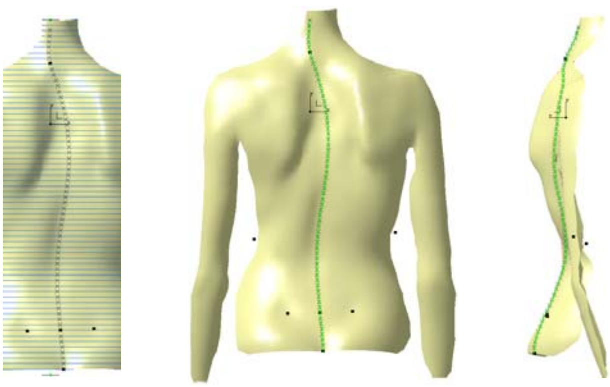
In order to represent and analyze the central spinal line and shape for diagnosis as well as characterization of the spinal deformity in adolescent patients with idiopathic scoliosis, after testing on 372 patients, we propose theuse of 5th degree B-splines [4].

2. MATERIALS AND METHODS

2.1 Central Spinal Line Representation

To achieve an optimum smoothness ofthe central spinal line and symmetry line of the dorsal surface, we have performed interpolation of vertices obtained by scanner using simple spline curves [5]. Then we obtained best-fit curves for the interpolated set of points. This interpolation enables us to have sufficient number of vertices to perform deformity analysis on the spinal line.

A set of focal points on the transverse profiles that was derived from the 3D scans of dorsal surface was used to measure "symmetry" as shown in figure 2.The line connecting these focal points may be single, double or triple curved depending on the angle of deformity and in ideal case it coincides with the line of spinal processus [1].

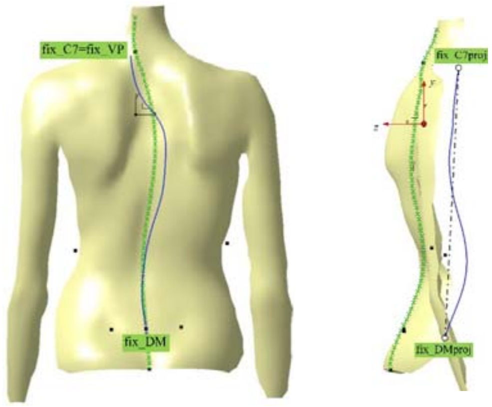


a) b)

Fig. 2. Interpolation of points of the symmetry line on dorsal surface a) posterior and b) sagittal view

We have defined the "angle of deformity (degrees)" as an angle at an instance (vertices) in the frontal plane, measured similar to Cobb's angle measurement method [4].

Central spinal line was derived by connecting centroids of all vertebral bodies in both frontal and sagittal plane [6,7]. Its mathematical representation allows us to localize inflection vertices for downstream curvature analysis of the spine and also to measure Cobb's angles to characterize idiopathic scoliosis (Figure 3). By projecting the spinal line on two planes (sagittal and frontal) analysis of its projections inflection points can be determined in places where the 2nd derivative is equal to Zero. Then the radius of the osculating circle be comes in finite. Analysis of the central spinal curve of deformity or its projections enables generation of a set of quantitative measures for physicians to determine positions and orientations of dislocated vertebrae, structure of deformity, and other postural parameters [6]. Having in mind that most of deformities occur between the spinal levels from L5 to C7, obtained 3D curve is segmented from projected *fix_C7*to*fix_DM* points (Figure 3) [8].



a) b)

Fig. 3. Segmentation of the spina lcurve from *fix_C7*to*fix_DM* a) posterior and b) sagittal view

Interpolation of the large number of near points consequently causes many changes of its curvatures. Approximation of the spinal curve in order to improve its smoothness is performed in PLM system CATIA using 5th degree of B-spline curve (Figure 4).

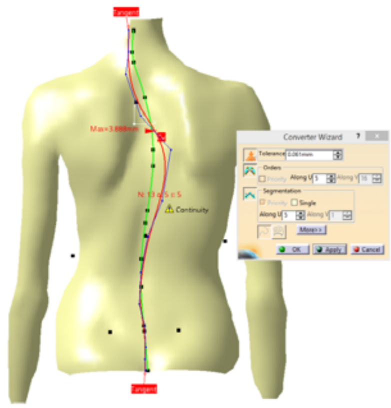


Fig. 4. Approximation of spinal line by B-spline

This stepis essential because the parameter of the segmented length determines the parameter of vertebral scaling factor. Unit scaling factor is normalized according to the Panjabi's anthropometric measures and recommendations [8]. In addition, the resulting curve segment *Split_L*is base for generating the skeletal CAD model (3D geometrical set) or reference 3D model to regenerate master model of the spine, inflection points, Cobb's and SOSORT-these angles in the sagittal and frontal plane, and also axial rotation of each vertebrae inthe transverse plane.

2.2 Influence of Order of Degrees of B-spline on Spinal Curve Approximation

The process of generating the spinal shape from 2D radiographic (x-rays) images is a complex one. Many authors have used a set of known anatomical landmarks which are easily recognizable in radiographic images to determine the inflection points (I_1, I_2, I_3, I_4 in Figure 5a) and the position of apex vertebrae of each segment (F_{12}, F_{23}, F_{34} in Figure 5d), required to represent the curve, curve's control vertices (lines of control polygon). For a detailed representation of the spinal profile on the frontal plane projection, the central spinal line should passes through the centroids of the vertebral bodies in x-rays, from 6 to 9 (8 to 10) representative points and should have C^2 continuity [9, 10] (Figure 5).

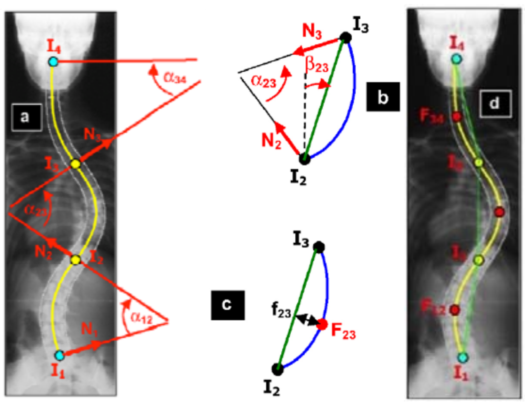


Fig. 5. Segmentation of frontal projection of spinal line by planar B-spline, adopted from [9]

The approximation of central spinal line was realized automatically to eliminate physicians' bias. The control vertices are generated directly from the 3D optical scan data of the dorsal surface. Reference lines, required to quantify Cobb's angle or angle of deformity, were automatically generated. Quality of the central spinal line - depends on the quality of interpolation and approximations of spinal line by B-spline and inflection points. Central spinal line in frontal plane is described by the ($n = 5$) 5^{th} degree of polynomial line and a method of analysis and generation of analytical Cobb's angles,as described in [10]. In this study we have used n^{th} degree spatial curve and quality control was performed with different degrees in approximation phase it self.

3. RESULTS AND DISCUSSION

3.1 Effect of Degrees of Approximation on Cobb's Angle Measurement

Table 1 provides a sensitivity of the central spinal curve of a patient, with different degrees of approximation ($n = 6$ to $n = 4$). A similar sensitivity analysis was performed on sagittal projection of spinal line as well, but not given here. After testing we concluded that for 3D representation of central spinal line in the space, 5^{th} degree B-spline is the most suitable [4]. By decreasing degree of B-spline, the formof the initial interpolation line will be significantly distorted, and by increasing, system will generate greater number of inflection points and unrepresentative Cobb's angles.

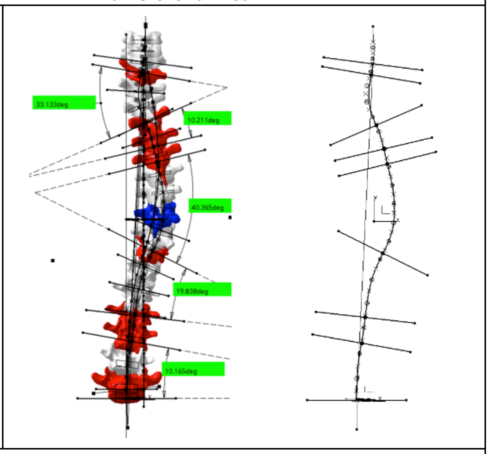
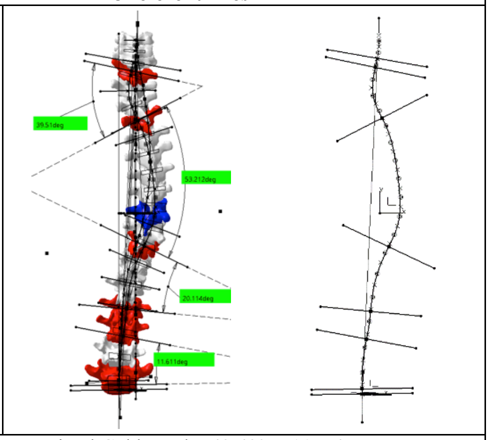
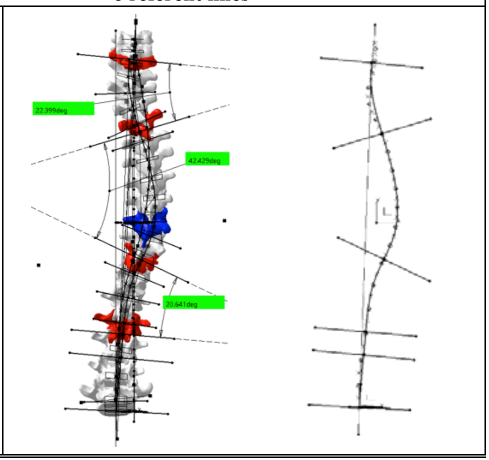
B-spline	Frontal plane	Spinal line
Maximal Cobb angle: **40.36º, T11-T6** **9 referent lines**		
Degree 6 $n = 6$		
Maximal Cobb angle: **53.21º, T11-T4** **8 referent lines**		
Degree 5 $n = 5$		
Maximal Cobb angle: **42.42º, T11-T4** **6 referent lines**		
Degree 4 $n = 4$		

Table 1. The influence of the degree of B-spline approximation on the smoothness and number of Cobb's angles

3.2 Deformity Curve Measures

Segment of the 3D spinal line denoted as a *Split_L* between dorsal anatomical markers *fix_C7*to*fix_DM* allows calculation of *ScalingFactor* parameter.

Those internal parameters of the spinal line are presented for 231 female and 141 male adolescents in table 2.

Descriptive statistics of spinal line lengths and scale factor for female and male adolescents

	N	Range	Min.	Max.	Mean	Std. Dev.
ScalingFactor Female	231	.39	.67	1.07	.89	.06
ScalingFactor Male	141	.44	.66	1.11	.93	.08
Split_L Female	231	197.73	336.73	534.46	442.2	32.17
Split_L Male	141	220.37	331.06	551.44	466.14	44.65

Table 2. Descriptive statistics of spinal curve parameters for 372 adolescents

3.3 Cobb's Angles in Frontal Plane

In table 1 comparative review of frontal spinal line projection for the same patient is presented. Cobb's angles in frontal plane were measured based on the generated segment *Split_L* of the spinal line. In the case of 6th degree of B-spline, software generated 5 different Cobb's angles (max=40.36º, T11-T6). In the case of 5th degree of B-spline, software generated 4 different Cobb's angles (max=53.21º, T11-T4). In the case of 4th degree of B-spline software generated 3 different Cobb's angles (max=42.42º, T11-T4). After testing, we concluded that 5th degree B-spline best fits given points, make smooth curve and doesn't distort projection as in a case of higher and lower degrees. Similar analysis can be performed in sagittal plane in order to quantify kyphosis and lordosis.

4. CONCLUSIONS

The diagnosis and treatment of adolescent idiopathic scoliosis rely on characterization of the spinal deformity. We have proposed a new method to quantitative measure the spinal deformity based on central spinal line that was computed from (i) generic 3D spine model, (ii) radiographic images, and (iii) 3D optical scan of dorsal surface. The central spinal line was generated in both frontal and sagittal planes to measure angular deformity of each segment of spinal curve (Cobb's angle). We have approximated and represented the central spinal line using 5th degree B-splines. Sensitivity analysis of degree and parameterson the deformity line was studied and found to be reproducible and satisfactory. Proposed methodology leads to more precise diagnosis and automated Cobb angles extracting in two planes, based on optical scans, compared to traditional methods where angles are measured manually on dimmed x-rays with low interobserver and intraobserver reliability. The representation needs to be evaluated on a larger data set with additional quantitative measures to be able to translate to clinical settingsacceptable in daily praxis.

ACKNOWLEDGMENTS

This research work is supported by the Serbian Ministry of Science and Technology under the grant III-41007: "Application of Biomedical Engineering in Preclinical and Clinical Practice".

5. REFERENCES

[1] Devedžić, G., Ćuković, S., Luković, V., Milošević, D., Subburaj, K., Luković, T.: *ScolioMedIS: Web-oriented information system for idiopathic scoliosis visualization and monitoring,* Computer Methods and Programs in Biomedicine, vol. 108, no. 2, p.p. 736-749, 2012.

[2] Piegl, L., Wayne, T.: *The NURBS Book*, 2nd ed., University of South Florida: Springer-Verlag Berlin, Heidelberg, 1997.

[3] Munira, M., Nur, N., Fazilah, A., Nooraizedfiza, Z.: *Review on Non Uniform Rational B-spline (NURBS): Concept and Optimization,* in International Manufacturing Engineering Conference (IMEC 2013), Bukit Gambang Resort City, Kuantan, Pahang, 2013.

[4] Ćuković, S., "Non-rigid registration of sculptured surfaces in Internet Environment", Doctoral thesis, University of Kragujevac, Faculty of Engineering, 2015.

[5] Hana, K., Hak, S., Eun, S., Choon-Sik, Y., Tae-Sub, C., Ho-Taek, S., Jin-Suck, S., Young, H., Sungjun, K.: *Scoliosis Imaging: What Radiologists Should Know,* RadioGraphics, vol. 30, p.p. 1823-1842, 2010.

[6] Berthonnaud, E., Dimnet, J., Hilmia, R.: *Classification of pelvic and spinal postural patterns in upright position. Specific cases of scoliotic patients,* Journal of Computerized Medical Imag ing and Graphics, vol. 33, p.p. 634-643, 2009.

[7] Stokes, I.: *Theree-Dimensional Terminology of Spinal Deformity. A Report Pesented to the Scoliosis Research Society by The Scoliosis Research Society Working Group on 3D Terminology of Spinal Deformity,* Spine, vol. 19, no. 2, p.p. 236-248, 1994.

[8] Cukovic, S., Devedzic, G.: *3D Modeling and Simulation of Scoliosis – an Integrated Knowledgeware Approach,* in 4th IEEE Mediterranean Conference on Embedded Computing - MECO, Budva, Montenegro, 2015.

[9] Berthonnaud, E., Dimnet, J.: *Analysis of structural features of deformed spines in frontal and sagittal projections,* Computerized Medical Imaging and Graphics, vol. 31, p.p. 9-16, 2007.

[10] Kanayama, M., Tadano, S., Kaneda, K., Ukai, T., Abumi, K.: *A Mathematical Expression of Three-Dimensional Configuration of the Scoliotic Spine,* Journal of Biomechanical Engineering, vol. 118, p.p. 247-252, 1996.

***Authors:* Dr Ćuković Saša, Prof. dr Devedžić Goran** University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia. **Mr Luković Vanja,** University of Kragujevac, Faculty of Technical Sciences, Svetog Save 65, 32000 Čačak, Serbia. **Prof. dr Nabil Anwer,** Paris Nord University, IUT Saint Denis, Place du 8 mai 1945, 93206 Saint-Denis Cedex, France. **Doc. dr Luković-Zečević Tanja,** Faculty of Medical Sciences, S. Markovića 69, 34000 Kragujevac, Serbia. **Dr. Subburaj Karupppasamy**, Singapore University of Technology and Design (SUTD), (EPD) Pillar, 8 Somapah Road, Singapore – 487372, Singapore.

E-mail: cukovic@kg.ac.rs; devedzic@kg.ac.rs vanja.lukovic@ftn.kg.ac.rs, nabil.anwer@ens-cachan.fr,, tanjalukovic_kg@yahoo.com, subburaj@sutd.edu.sg