Title:
Rigid 3D Registration Algorithm for Localization of the Vertebral Centroids in 3D Deformity Models of Adolescent Idiopathic Scoliosis

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Introduction:
Scoliosis is a highly complex 3D musculoskeletal disorder (MSD) of the spine that greatly affects the patient's health and quality of life, including functional limitations with secondary complications such as respiratory and circulatory dysfunction, pain, and cosmetic changes. Scoliosis affects 2-4% of the global population, and almost 80% of the developed cases are of an unknown reason (i.e. idiopathic) [4], with an estimated prevalence of 36 million new patients worldwide by 2050 according to the WHO. Adolescent idiopathic scoliosis (AIS) is known as a deformation of the spinal curve of more than 10º angle, measured traditionally on standing planar or biplanar radiographs, using the Cobb technique [3]. To-date, the so-called Cobb angle is considered as the key parameter in AIS diagnosis and acts as a guide for treatment, but describes only the 2D curvature of the deformity in the anterior/posterior and/or sagittal plane from 2D X-ray images with significant intra- and inter-observer variability and errors.

In recent years, innovative 3D optical systems have been considered as alternatives to X-ray imaging for estimating the 3D spinal curve that passes through centroids of each vertebral body (Middle Spinal Line - MSL) and vertebral axial rotations [6], [1]. A surface topography method, e.g. rasterstereography, is less expensive, non-invasive and non-ionizing technique through which the curvature of the spine is modelled to allow an estimation and evaluation of deformity-related changes of the digitalized patient's back surface using only light as a medium. New studies have shown that certain deformity indicators (Cobb angle) calculated using optical methods have a relatively high reliability [9],[10]. However, to-date, none of these diagnostic approaches have been applied to calculate other internal parameters of the deformity, and still neglect the 3D complexity of the internal spinal structures.

A generic, state-of-the-art about 3D CAD model of the spine (GMS) recently, has been developed at the University of Kragujevac to simulate the 3D nature of the deformity and to estimate internal biomechanical properties and indicators of AIS. GMS is scalable and registerable model of the spine to the 3D digitalized surfaces of the patient's back, optically (non-invasively) scanned [4]. Also, a novel computational algorithm embedded in the state-of-the-art ScolioSIM1.0 tool for markerless and contactless detection of the key anatomical landmarks on a patient's back was developed and tested on partial X-Ray images [4]. These technical solutions resolve our challenge to generate a 3D patient-specific spine/deformity (PSS) model and to extract internal deformity parameters from an external surface only.

<u>Main Idea:</u>
We proposed a non-invasive 3D methodology and a system to quantify deformity measures using patient-specific models generated from patient's dorsal shape, anatomical landmarks, curve of surface asymmetry and middle spinal curve generated from optical 3D scan data. Developed system is created using knowledgeware technology and VBA macros implemented in PLM system of CATIA V5 to perform these measurements with minimal human intervention. General methodology for obtaining a patient specific 3D model of the deformity is given in Fig. 1.

Knowledgeware Technologies
We used PLM system of CATIA V5R20 to automate the methodology with an in-built VBA (VB software is given in [7]) scripts called *ScoliosisSimulator-3DSpinalRegistration.catvba.* This macro processes the patient's optical scan of dorsal surface, generates elements of CAD skeletal model based on a generic parameterized CAD 3D model of spine (by rigid registration) and generates key parameters to quantify deformity [4],[5]. We implemented VBA macro for generating and visualizing reference elements of 3D skeletal model on the spinal curve. For this purpose, we used Turner-Smith's rule, which localize peaks of spinal processus on the dorsal surface. The VBA macro produces a set of diagnostic parameters exported in a separate *.xls file for further analysis.

3D Registration of the Spinal Model with Dorsal Surface – "Patient-Specific" 3D Deformity Model
Generic 3D model of the spine is adaptable and registerable to the dorsal surface. Using *ScoliosisSimulator-3DSpinalRegistration.catvba* macro, "patient-specific" model of deformity is be generated. Scaling factor modifies each vertebral model in 3 directions according to rigid registration principle (3D to 3D), Fig. 1.

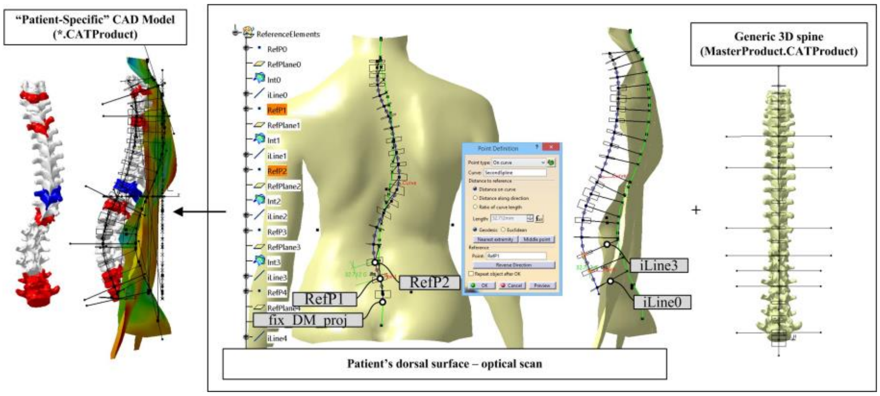

Fig. 1: Registration and referencing of the generic 3D model of the spine to the dorsal surface - "patient-specific" model of the deformity.

This model generates a set of internal and external parameters. Particularly important are SOSORT-these angles, Cobb angles, transpositions of vertebral body centroids and intervertebral discs. Transpositions have negative sign ("-") if the vertebral bodies are dislocated left from CVS line (Central Vertical Spinal Line), and positive ("+") if centroids are right from this line. The vertebra which is in a sense of absolute value, the most dislocated is called apical vertebra. This vertebra belongs to the primary curve and is around of the peak of that curve.

To localize centroids of each vertebra and transform 3D vertebral models to make them "patient-specific" we implemented registration technique. Vertebral models are then registered over skeletal model of the deformity, as shown in Fig. 3.

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Registration:

Image Registration is a set of transformation methods used to fuse two 2D images or 3D point clouds in a common coordinate system. It is usually considered that raw images or 3D clouds of the target object are acquired in different time and perspective, with the same (intramodal) or different modalities (intermodal). In the case of 3D-3D registration it is necessary to have corresponding points, lines or surface features, internal or external anatomical landmarks. Vertebral models of the generic spine are reconstructed from CT slices and represent point clouds of the real vertebrae. We used CATIA to make scalable and parametric models adaptable to various patient-specific conditions, including congenital changes on vertebral shapes. These models are statistical and correspond to standardized Panjabi's measurements [4].

In this paper, we apply 3D registration algorithm to transform vertebral models and adopt their positions toward 3D back surface. As we work with bone anatomical 3D models, we focused on rigid transformation algorithms. To register their centroids on the middle spinal line and orient them towards 3D back surface we apply basic 3D transformations.

General Methodology

We consider the alignment of two vertebral shapes (point clouds) as a probability density estimation problem defined by Myronenko. One of the point clouds is GMM (Gaussian mixture model) centroids and another one is target point cloud [2]. Here is the basic notation as it is defined in [8]:

- D - dimension of the point sets; N, M - number of points in the point sets;
- $X_{N\times D} = x_1,...x_N{}^T$ - the first point set; $Y_{M\times D} = y_1,...y_M{}^T$ - the second point set (GMM centroid);
- $\tau = Y,\theta$ - transformation τ applied to Y, where θ is a set of the transformation parameters;
- I - identity matrix;
- 1 - column vector of all ones;
- $d = (a)$ - diagonal matrix formed from vector a.

Rigid registration allows rigid transformations: translation, rotation and uniform scaling factor [8]. For this type of registration, transformation of the GMM is required $\tau\ y_m;R,t,s\ = sRy_m + t$ where $R_{D\times D}$ is a rotation matrix, $t_{D\times 1}$ is translation vector and s is scaling factor. In this case, the objective Q– function depends on rotation, translation and scaling factor and has the form Eqn. (1):

$$Q\ R,t,s,\sigma^2\ = \frac{1}{2\sigma^2}\sum_{n=1}^{N}\sum_{m=1}^{N} P^{old}(m \mid x_n) \,||\, x_n - sRy_m - t \,||^2 + \frac{N_P D}{2}\log\sigma^2 \tag{1}$$

Where: $R^T R = I$ and $\det(R) = 1$

In the given equation first part is similar to form of absolute orientation problem.

Application of Rigid Registration to AIS Modelling

To simulate scoliosis of a specific patient, it is necessary to have a fully assembled model of the physiologically normal spine with 20 vertebral models. This CAD model is a parametric master model created in CATIA and represents the S shaped spine with normal lumbar lordosis, thoracic kyphosis and cervical lordosis.

Master 3D model of the spine is adoptable to 3D dorsal skeletal models generated using ScoliosisSimulator-3DSpinalRegistration.catvba macro illustrated in Fig. 2(b). This is done by rigid transformations using embedded formula Eqn. (1) over common referencing elements of the skeletal model and vertebra (centroid and vertebral axes).

Fig. 2(a). illustrates referencing and orientation of the lumbar model L2 towards digitalized dorsal surface and automatic creation of the geometrical relations among geometrical elements in assembly model (e.g., coincidence).

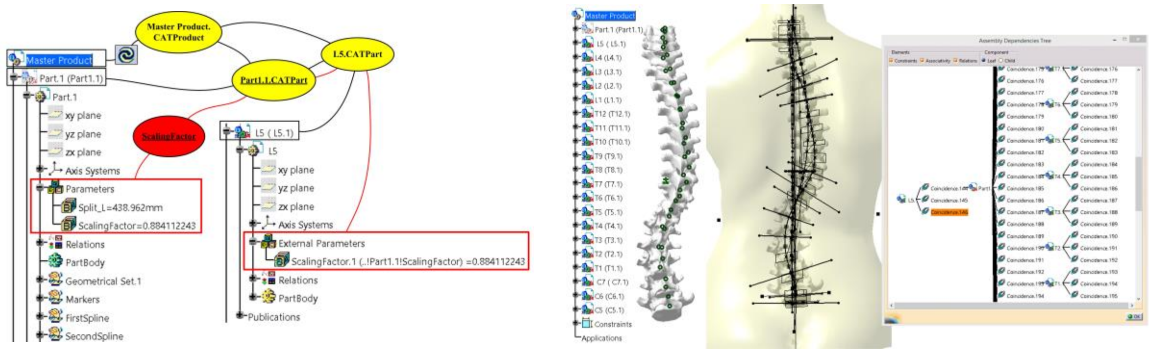

Fig. 2: (a) Initialisation of the rigid registration process, (b) AIS patient-specific assembly model in CATIA with model tree and geometrical associations for a 14 years old female patient.

VBA script, we created all dependences between skeletal deformity model of dorsal surface and enables a strong multi-modular associations and built-in knowledge with vertebral models from the master assembly (*Master Product.CATProduct*). Initialization of the registration process is determination of the scaling factor and its transfer from skeletal deformity model to each vertebra model. Standardized modelling techniques, like publication, "child-parent" modelling technique as well as external parametrization in assembly module, also, are implemented. After registering all vertebral models towards surface, we have a full 3D deformity model of AIS, or "patient-specific" deformity mode. For this purpose, we used Turner-Smith's rule, which localize peaks of spinal processes towards the dorsal surface. 3D CAD model of deformity and *ScoliosisSimulator-3DSpinalRegistration.catvba* macro are integral part of the system ScolioMedIS, the information system for monitoring and diagnosing scoliosis, for online AIS diagnosis and monitoring.

Results:

The system produced a set of diagnostic parameters that are displayed in the special branch of the CAD elements tree, but also exported in separate *.xls file for downstream analysis. Besides, it generates printable report on the performed analysis (Fig. 3.).

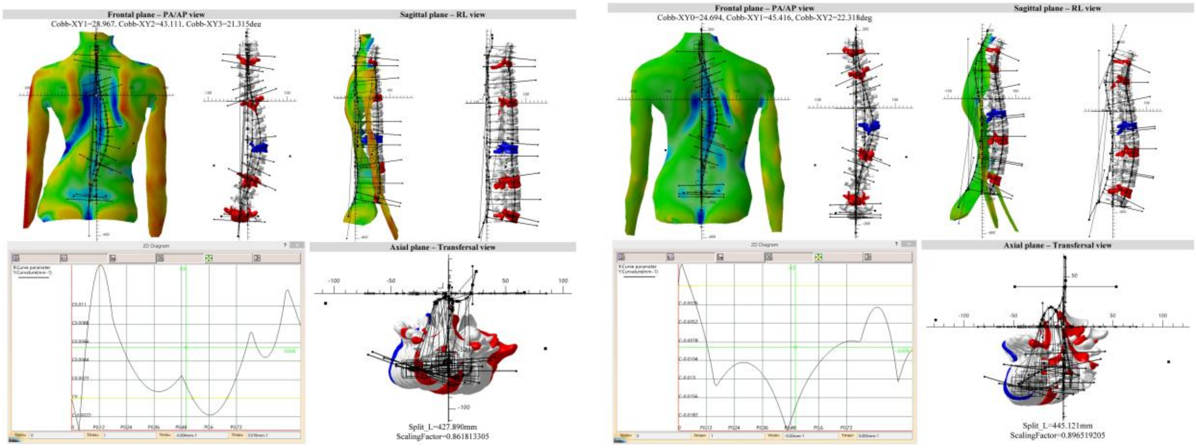

Fig. 3: Reports and visualizations of the Patient-specific deformity models for two AIS patients.

Full visualization of the deformity is performed using Knowledgeware technologies and rigid registration algorithm in standard CAD environment. As a result of the registration process and mathematical calculation we have many parameters generated in the sub-processes. We successfully tested abovementioned system on 372 patients in adolescence optically diagnosed from 2015 to 2017. Following patient cases are examples of two female patients with moderate thoracic scoliosis:

Conclusions:

This paper presents a part of the results related to our development of methodology for the diagnosis of spinal deformities. It is based on the application of methods of surface topography to reduced exposure to X-rays for patients suffering from idiopathic progressive scoliosis, aimed at the elimination of radiation. The developed approach is based on the registration algorithm and application of knowledgeware technology, as the integrator for patient-specific 3D modelling, visualization, simulation and monitoring of scoliosis. Spinal deformity modelling is based on generic 3D model of spine, generated from CT scans, which can be regenerated and adapted to the model of patient's dorsal surface. The developed system is tested on a representative number of adolescent (372), on models of their dorsal surfaces and results indicate that the system is robust and it can reduce the need for radiographic examinations.

The protocol, we proposed, takes into consideration the 3D nature of the deformity, with special accent on the sagittal plane and axial rotations, which is usually given insufficient attention in everyday clinical practice. Our system excludes subjective assessment and any writing/reading error, and it can be expected that this protocol will gain high value when measuring on subjects with scoliosis deformity.

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