A Computational Algorithm for Scoliosis Assessment from a Noninvasive 3D Body Scanner * **

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Abstract. Scoliosis is characterized by three-dimensional deformities of the spine, showing a lateral curvature of the spine of at least 10° and axial rotation around the vertical body axis. This inside deformation has an impact on the outside torso contour. For the diagnosis of scoliosis, in addition to clinical examinations an X-ray is required at the first consultation with an orthopaedic specialist. In case of fast progression of scoliosis specially during growing stage, regular clinical monitoring is required, including follow-up X-rays. As a consequence of frequent X-rays, patients are often exposed to significant ionizing radiation and have a higher risk of radiation-related health problems. To reduce the number of X-rays a 3D body scanner is proposed as an ionizing radiation-free method, supplementary to clinical examinations, for assessing scoliosis and its progression. A mathematical method is proposed in combination with a self developed model of rib cage and vertebral column to analyze the spinal curvature from the image obtained from 3D body scanner. Here we present the idea, challenges and possible solutions at the example scan from a healthy person. In future, the proposed methods will be transferred and applied to patients with different kinds of scoliosis, as an alternative for X-rays.

Keywords: Scoliosis · Non-invasive · Mathematical calculation.

1 Introduction

Scoliosis is a medical condition characterized by three-dimensional (3D) spinal deformities, showing at least 10° of lateral curvature in the coronal plane and

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a vertebral rotation [10, 16]. Rotation of the vertebrae around the vertical axis results in an asymmetric torso shape. In addition, scoliosis can entail difference in shoulder height and pelvic discrepancy. In general, scoliosis has a multifactorial etiology and can be broadly categorized as idiopathic neuromuscular, syndrome related, and congenital. The most common type of scoliosis is idiopathic, in which the exact etiology is still unknown [4].

Adolescent scoliosis, either idiopathic or neurogenic, is one of the most common pediatric diseases, which has a higher risk of progression and aggravation of the scoliotic deformities. The severity of deformity is usually assessed by radiography examinations, and quantified by the Cobb angle [5] of the spine. The change in the patients' Cobb angle over time then can be relevant for the type of treatments and to assess the effectiveness of the provided treatment. As a result of frequent radiographies, patients are often exposed to significant ionizing radiation and have a higher risk of radiation-related health problems in their future. In order to minimize the effect of radiation exposure to patients, a variety of non-invasive methods, measuring devices and characterization standards have been developed [13]. They yield information supplementary to that provided by X-rays. Examples of such systems and methods include the Moiré-fringe mapping [2], the integrated shape imaging system (ISIS) [1], the Quantec scanners [17], the laser triangulation [12], an ultrasound system [18] and raster-stereography systems, using structured lights of different wavelengths [6, 11]. Methods based on torso inclination and rotation angles, as well as surface topography techniques based on structured light measurements, are currently the most employed in clinical practice [7, 13].

For the same purpose, a 3D body scanner has been developed with a camera system [15] for the assessment of scoliosis, especially for patient with cerebral palsy (CP) who suffer very often from scoliosis. The scanning procedure with the 3D body scanner is very fast and does not need any preparation time, since it does not use any marker. The fast scanning procedure is a great advantage in comfort, especially for patients with disabilities like CP, because they have to hold their position and posture only for a short period of time. The body scanner provides a three-dimensional image of the torso. The task then, is to develop analysis tools that can quantify the torso asymmetries from the 3D images of the torso in a manner similar to that generally done by X-rays to characterize scoliosis.

For this purpose, a basic skeletal structure of the essential components of the ribcage and vertebral column have been modeled with computer aided design (CAD) software [8], hereinafter referred to as bony model. In a first approach, the method presented here consists of a semi automated procedure of extraction of some quantitative parameters from the scan image and from the bony model, in different human anatomical planes. The scanner system does not provide any fixed reference frame. For future comparison it is therefore necessary to define a fixed reference frame and/or to find parameters which are invariant under rotation and translation of the coordinate system. The quantities, introduced here, hence were defined with respect to the individual main human body planes, which are independent from the orientation of the human body in the lab coordinate system.

Even though the method presented here based on the scan image of a healthy person and the bony model is presented for a normal configuration of human spine, it is intended in the future to generate patient specific spinal configurations by means of simulations. Generally, an X-ray image is essential, as a standard of treatment for the first appointment with an orthopaedic specialist, in order to confirm the suspected diagnosis after clinical examinations and to verify the severity of scoliosis to start appropriate treatment. In perspective of future clinical applications, the first time taken X-ray will be used in order to get the initial configuration of the vertebral column for the simulation of the bony model. On the same day, a body scan image will be captured. Then the scan image will be oriented according to the quantities introduced here to obtain the best match with the bony model and put them together in the same reference frame. Later in the follow-up examination, in addition to clinical examinations, a scan image will be captured and natural growth will be noted in case of young patients. In order to account the patient's body change due to natural growth, initially obtained bony model will be scaled along the principle axes and compared with the scan image. Thus the model will replace the X-ray image in the follow-up examination. If there is a mismatch between the model and the follow-up scan image, the model will be simulated to obtain a good match with the scan image in different planes. The new approximated vertebral body positions from the bony model will then give the spinal curve normally obtained from X-rays. Thus one has the possibility to reduce number of follow-up X-rays.

2 Materials and Methods

2.1 Scan Image and Bony Model

Here we analyzed a torso image of a 25 years old healthy male, obtained using the 3D body scanner. At the beginning, parts not belonging to the torso contour, i.e. the portion of head, arms, were removed from the image. Only the torso part of the image was extracted for analysis in terms of 3D Cartesian coordinates (see Fig. 1(a)). The geometry of a bony model of rib cage and vertebral column of an average human, based on real geometry and anatomical parameters [3, 9], was constructed using FreeCAD, an open-source program to design real-life objects [19]. The natural S-type shape of the course of the vertebral column in the sagittal plane was considered [8]. The geometry of the model can be adjusted according to the individual anatomical specifications of male and female. The model has also the possibility to scale along the principle axes to account for the effects of individual body shape and sizes of the patient [8]. Figure 1(b) shows the bony model of an average male.

The dimensions of the bony model for a male and the extracted region of the scanned image were then normalized along the principle axis in between 0 and 1 (see Fig. 1). 2D cross sections transverse to the vertical body axis were extracted from the model and from the scan image. Their contours or the outlines of this

2D transverse cross sections were presented in terms of Cartesian coordinates (see Fig. 2). The positions of the spinous processes (marked as 'SP' in Fig. 2 (upper panel)), were located from the scanned image, by finding the dip in the back part of the 2D cross sections transverse to the vertical body axis. A self developed analysis tool extracted the 3D coordinates of the spinous processes positions following the automated algorithm described in [14]. This automated method used the position of the centroid of transverse cross section, computed as the arithmetic mean considering all the coordinate points belonging to that particular transverse cross section. In case of the bony model the centroid of a transverse contour was also computed from the arithmetic mean of all coordinate points in that plane. Since in each transverse plane the majority of coordinate points are located near the backside, that is the lower part in Fig. 2 (lower panel), it turned out that the centroid falls into the region of the vertebral body. Lower panel of Fig. 2 shows this point marked as 'C'. The 3D coordinates of the spinous processes positions and the vertebral bodies regions are marked at all vertebral levels (T1 to L5) in the scanned image (see Fig. 1(a)) and the model (see Fig. 1(b)), respectively.

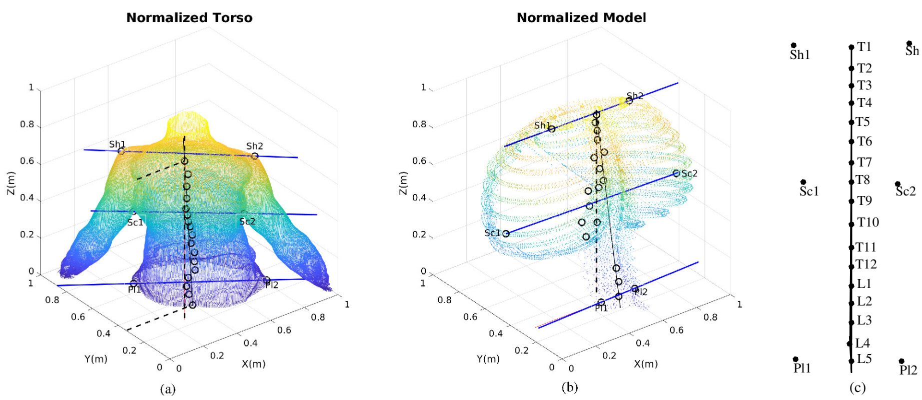

Fig. 1. (a) 3D image of a healthy male obtained using the 3D body scanner. (b) The bony model of ribcage and vertebral column of an adult male, based on anatomical geometry and dimension parameters after [3, 9]. (c) Schematic diagram of the marker positions. In subplots (a) and (b) automatically and manually detected marker positions are indicated by black open circles and in subplot (c) with black filled circles. Shoulder line (Sh1-Sh2), scapulas line (Sc1-Sc2) and pelvic lines (Pl1-Pl2) are also indicated from top to bottom along the vertical body axis in subplots (a) and (b).

In addition to spinous processes positions left and right extreme points on the shoulder level (Sh1, Sh2), on the scapulas level (Sc1, Sc2) and on the pelvic level (Pl1, Pl2) were manually extracted from both the model and the scanned image. For the model, T1, T8 and L5 vertebral levels were assumed to be at shoulder, scapulas and pelvic levels respectively. These points are also marked in

Fig. 1 with black open circles. The 3D coordinates of all these marker positions, indicated in Fig. 1 (extracted automatically and manually), were picked for further analysis. Figure 1(c) shows a schematic diagram of the extracted marker points where 3D coordinates were picked.

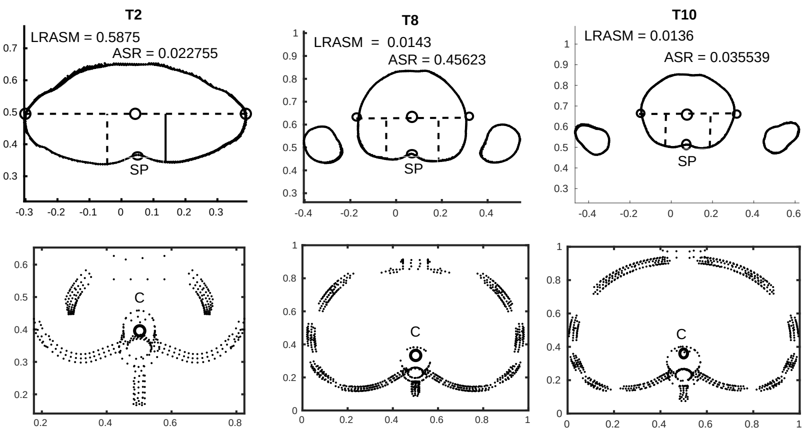

Fig. 2. Examples of three transverse cross sections of torso contours extracted at different vertical levels. Upper panels: transverse cross section from the scan image. Indicated are the values of the two symmetry parameters characterizing the torso contour shown. Lower panels: transverse cross sections from the bony model.

The principle axes of the Cartesian coordinate system (X,Y,Z in Fig. 1 (a) and 1(b)) of the bony model are parallel to the normals of the main anatomical planes of the human body. That is, any anatomical position of the bony model can be described with respect to these three planes:

– the transverse plane parallel to the ground separates the body into top and bottom halves
– the coronal plane perpendicular to the ground separates the front (anterior) from the back (posterior)
– the sagittal plane is perpendicular to the transverse and coronal and separates the left from the right.

For the scan image the situation is more difficult. Since the camera of the scanner system needs to be adjusted according to the individual height and standing position of each patient, the viewing axis and thus the camera angle relative to the patient is different for all scans at all times. The scan image thus always has an oblique coordinate system, with different obliquity at each and every time. Therefore it is important to have the exact angular information about the obtained 3D torso image initially for future comparison.

The 3D coordinates of the marker positions were used by the analysis program to identify and check the orientation of the scanned torso in relation to the laboratory coordinate system and to compute the parameters described in the next section.

2.2 Analysis Parameters

The analysis parameters introduced here were computed independently for the scan image and for the bony model. These parameters were designed to identify and quantify the characteristics of scoliosis from the scan image with the help of bony model. They were intentionally defined in relation to the three main body planes and thus independent of the coordinate system. Further, thereby the impact of growth and posture is reduced, which is important for future applications to adolescents. The parameters introduced here are not very typical in medical literature, but the way the tool is designed has the possibility to evaluate the standard parameters used in medical literature e.g. thoracic kyphosis, lumbar lordosis.

- **Extraction of specific lines from the scan image and from the bony model:**
  (a) *Vertebrae line or principal axis:* The vertebrae line or principal axis was defined as the straight line between the positions of the spinous processes at the levels T1 and L5 for the scanned image and accordingly between the corresponding vertebral bodies at the bony model.
  (b) *Vertical and horizontal line:* A vertical line parallel to z axis and a horizontal line parallel to x axis were defined at positions T1 and L5. In principle, at any marker position these lines can be created.
  (c) *Shoulder, Scapulas and pelvic line:* Straight lines were created at shoulder (Sh1–Sh2) , scapulas (Sc1 –Sc2) and pelvic levels (Pl1–Pl2), connecting left and right points.
- **Definition of the parameters:**
  (a) *Torso inclination angle:* Angle between the vertebra line and the vertical axis containing T1 was defined as torso inclination angle. This is a parameter in sagittal plane. In principle, it would be possible to divide the sagittal plane by thoracic and lumbar part.
  (b) *Pelvic obliquity:* Angle between the pelvic line (Pl1–Pl2) and the horizontal line at L5 was defined as pelvic obliquity. This is a parameter in the frontal plane.
  (c) *Shoulder obliquity:* Angle between the shoulder line (Sh1–Sh2) and the horizontal line at T1 was defined as shoulder obliquity. This one is also a parameter in the coronal plane.
  (d) *Pelvic Rotation:* Angle between the pelvic line (Pl1–Pl2) and scapulas line (Sc1 –Sc2) was defined as pelvic rotation. This is a parameter in transverse plane.
  (e) *Left-right area asymmetry:* The regions spanned by the contour of the transverse cross sections were divided by left and right area following

the similar approach published [14]. A left-right asymmetry parameter (LRASM) based on these areas was calculated as follows:

$$LRASM = abs\Big(\frac{L-R}{L+R}\Big), \tag{1}$$

where L and R are the areas on the left and right sides to the spinous processes positions respectively of the transverse cross sections.

(f) *Aspect ratio difference:* This parameter computes the difference between the height and width ratios at two sides of the transverse cross sections following the same approach described in [14]. The aspect ratio difference is defined as:

$$ASR = abs\Big(\frac{\text{Right side height}}{\text{Right side width}} - \frac{\text{Left side height}}{\text{Left side width}}\Big). \tag{2}$$

The method was developed by using Matlab2019a (The MathWorks, Inc., Natick, MA, USA) and the meshlab software.

3 Results and Discussions

Figure 1(a) shows the scan image from a healthy person and Figure 1(b) shows the bony model for an average male. In Figure 1(b) the normals of the main anatomical planes of the human body are parallel to the principle axes of the lab coordinate system. In case of the scanned image (see Fig. 1(a)) the normals of the main anatomical planes however are not parallel to the principal axes of the lab coordinate system.

Table 1 lists the corresponding angular parameters, computed for the case of the bony model and the scanned image. For the bony model, the value of the torso inclination angle reflects it's natural S-type shape of the course of the vertebral column in the sagittal plane. On the other hand, the S type nature of the course of the vertebral column for the case of scan image can be detected by the torso inclination angle ($\sim 9°$). Quite a good matching of this value indicates this parameter might be a good choice to capture the change in scoliosis in the sagittal plane. However, the larger values of pelvic obliquity and shoulder obliquity of the scan image imply that the image's anatomical plane is obliquely placed with respect to the lab coordinate system. This is the main difficulty of the presented method to separate the effects of body change due to the change in scoliosis from the effects due to the scanning procedure (different position of the patient, camera etc.). Therefore, for future comparison, either the follow-up image should have the same orientation with the initial one or our analysis system needs to set a fixed reference frame. For the first option, more automation of the present program, specially automatic detection of shoulder points, pelvic points and scapulas points, will help, so that the obtained image can be simultaneously checked and patient position can be adjusted to reproduce the orientation of previously obtained image. For the other option, the analysis tool can transform the basis of the coordinate system into the bony model's basis. Either one of

Table 1. Angular parameter values for the bony model and for the scan image at different planes.

Parameter	Value from the model	Value from the scan
Torso inclination angle	10°	8.88°
Pelvic obliquity	3.82°	34.48°
Shoulder obliquity	2.61°	41.22°
Pelvic rotation	5.02°	2.58°

these is necessary to capture the change of torso shape due to scoliosis, which is our end aim.

Figure 2 illustrates transverse body contours, extracted at T2, T8 and T10 levels of the vertebral column. The upper panel shows the 2D transverse cuts from the scan image and the lower panel shows the same for the model. The corresponding left-right asymmetry (LRASM) and aspect ratio difference (ASR) parameters of the cross sections extracted from the scan image are given in the annotations. The positions of spinous processes and approximated vertebral body positions are depicted with the black open circles. Qualitatively there is a change in the shape of the contours, from the scanned image from the left to the right panel. These changes in shape are reflected in a change in the values of the parameters: the LRASM parameters decrease continuously from left to right. In contrast the aspect ratio difference asymmetry increases from the left to the center panel and decreases to the right panel. The equivalent values of the symmetry parameters can not be calculated for the transverse cross sections of the model (lower panel), because the scattered points are not continuous and not equally distributed at all levels. Proper fitting function for shape matching, at this level, will help to calculate the above mentioned symmetry parameters from the bony model.

Our previous study supports the concept of these two symmetry parameters by finding quite a good correlation with the apex position of scoliosis, when comparing with computer tomography data set [14]. Therefore, best matching with the 2D transverse cross sections from the bony model and 2D transverse cross sections from the scanned image at different vertebral levels will help to predict the position and orientation of vertebral body from the scanned image, and finally the course of vertebral column.

The current, as well as other non-invasive methods, however, cannot completely replace the conventional and established methods (e.g. X-ray, MRI) in the medical assessment of scoliosis, specially when surgical decisions are involved. Further X-rays might be necessary when significant changes in scoliosis are recognized clinically and also in the method presented here. In principle, the idea introduced here can be implemented to get a large number of quantities or indices along the vertebral column. Therefore there might be a good chance to find a well correlated index with the standard method like Cobb angle. An implementation and development of such methods requires, however, analysis of a larger set of data. The idea here described constitutes nevertheless a preliminary step in this direction. In general, the present scanner system might have the potential to reduce the number of X-rays in follow-up examinations, which is needed for adolescents with scoliosis.

4 Future work

- To reduce the effect of camera position and different standing positions of the patients, more automation of the presented method will be considered and several experimental measurements with healthy participants without scoliosis will be done to calibrate the scanning procedure against external perturbations, like the effect due to the position of the camera, position and posture of the patient etc. These steps will be considered in our future work.
- Finding an algorithm for shape matching for the 2D transverse cross sections from the bony model and from the scan image will also be considered in future work.
- Simulation of the bony model following finite element method simulation will be done in future to get the distorted configuration of vertebral column.

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