Geometric properties of the 3D spine curve

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Abstract. Through a 3D reconstruction of the human back surface using structured light techniques, we study the properties of spine curve by means of a set of parameters related to measures commonly applied in medicine. In this way, descriptors for measuring the abnormalities in the projections of the *front* and *sagittal* planes can be computed. We build the spine curve in 3D and analyse the behaviour of the *Frenet frame* when along the curve the deformation processes in idiophatic scoliosis appear.

Keywords: Biomedical pattern analysis, image analysis, structured light.

1 Introduction

Serious deformities in the human spine are present in the 0.3 percent of the population [5]. The most common deformity is *scoliosis*: an abnormal lateral curvature of the spine of congenital origin or caused by trauma or disease of the vertebrae or hip bones. This is first noticed as a result of the changes that occur in the shape of the human back during the adolescent growing season. The characteristic feature is the disfiguring hump, caused by the rotation of the vertebrae and ribs, that is presented together with a lateral bend of the spine.

In some few cases, the deterioration of the spine occurs quickly, so a prevention of theillness is necessary as soon as possible. Unfortunately, the only means of assessment has been unadvisably frequent x-ray examinations. Through a accuracy clinic visualisation on the back surface of the cosmetic deformity, the illness can be diagnosed and the treatment started, although this deformity already involves an important development of the illness. Aiming at this, several methods of surface shape measurements have been previously used, ranging deformation tests, photographic methods, and direct computer input from a special scanner [7, 12, 13].

In the present work, we describe how a non-invasive method like structured light can be used to detect the illness through the study of the spine deformity to the shape of the back surface. We examine how the vertebral deformities reflect on the back surface and what relation do they have to the information obtained with the x-ray images. We make a reconstruction of the spine curve and explore the projections of the curve in the *front* and *sagittal* planes of the body. The intrinsic parameters of the curve and its corresponding properties are also obtained. We use the nomenclature of Ponsetti and Friedman [8] to classify the different types of scoliotic curves[1].

2 Extraction of the curve parameters

2.1 Reconstruction of the back surface

Through a method based on structured light [1, 11], we obtain a reconstruction of the back surface by means of the deformation of a known structured pattern that is projected over the objects in the scene (object grid). So, we can obtain the 3D position points of the object surface and make the correspondence between points or regions in smooth surfaces as it is the case of human backs.

In order to establish the deformation, and in addition to the object grid, the utilised procedure requires the digitisation of the images of the grid projected on a flat surface (screen) placed, respectively, behind the object (back grid), and in the front of the object (front grid). This method allows to achieve the correspondence of the grid nodes on the three images (back grid, front grid and object grid) and to obtain the values of z (depths) for the nodes in the object grid. This procedure needs to be made just once for each setup for calibration purposes.

In the surface reconstruction phase, we analyse the list of the nodes in the object grid and calculate the co-ordinates of the intersection points of the straight pattern lines for the front grid and back grid images. This way, we get the positions (x, y, z) of the grid nodes as they are projected on the object and we can build a depth map for the grid nodes on the surface of the human back, as it is observed in Fig. 1. The rest of points on the surface are reconstructed by a parametric approximation. The evaluation of the errors during the measurement process have been estimated in less than 4 %.

2.2 Spine curve positioning on the surface

Once we have the back surface depth map, the objective is to obtain the curve that passes over the vertebrae beneath the skin. Two data sources are utilised to obtain this spine curve:

1. Locate on the back surface the vertebral spinous processes, from C7, also named the *prominent vertebra*, to the last lumbar vertebra L5[2] (see Fig. 1). In practice,

[1] This nomenclature makes a classification of the spine shape according to the position of the principal curve in the *front* plane: cervical-thoracic, thoracic, thoraco-lumbar, double major, and lumbar.

[2] The vertebrae are enumerated from the head to the hip with the following sequence: Cervical (C1...C7), thoracic or dorsal (D1...D12) and lumbar (L1...L5). The vertebrae C7 and L5 are the extremes of the spine curve considered. Thus, only thoracic and lumbar zones are considered in this work

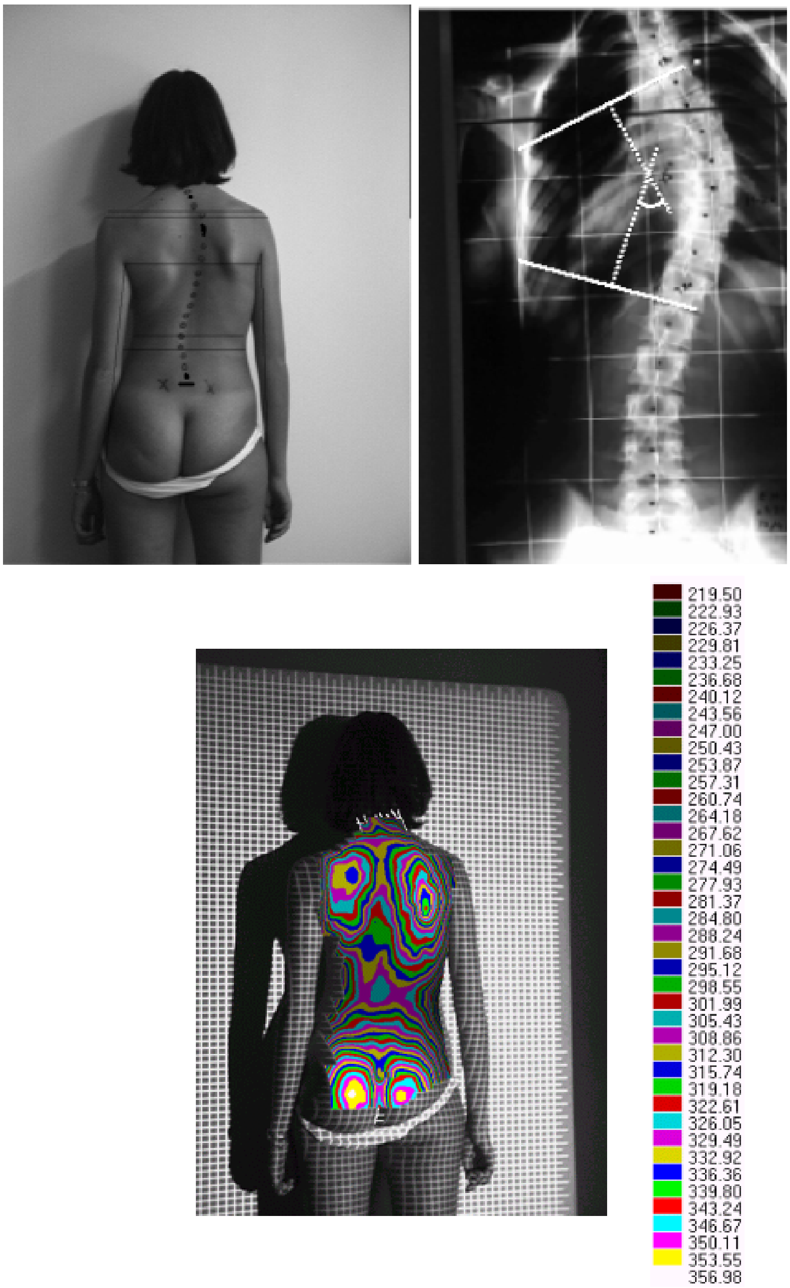


Fig. 1. (Top-left) Clinical image of a patient with a severe thoracic scoliosis. The vertebral spinous processes are marked on the skin. (Top-right) A radiography of the same patient. (Down) Topographic representation of the back surface with the values of z displayed in millimetres (on the right, in colours, not displayed).

marking the patient takes only one minute and the landmarks can be positioned with an accuracy of ± 5 mm.

2. The study of the shape of the spine curve in x-ray images. In this case, we have a real knowledge about the displacements of the vertebrae and their rotations through the projection of the vertebral pedicles. Also, we can locate a centre point for each vertebra in the radiograph (see also Fig. 1) and, by means of an alignment process [3], a transformation of scale, rotation and translation is made to put the points of the spine shape in the x-ray image over our depth map.

2.3 Study of the *front* and *sagittal* planes of the curve

When the specialists study the x-ray image and assess the vertebral rotation angle, they utilise the *Cobb angle*, defined as the angle between two vertebral plates: those having a higher and opposite inclination respect to the horizontal plane (see Fig. 1, top-right). So, only if the Cobb angle is larger than 12 degrees in x-ray image, the specialist considers that there is a scoliotic process. In our case, we study projections of the spine 3D curve in the *front* and *sagittal* planes of the body. One measurement associated to the Cobb angle in the *front* plane is the *lateral asymmetry* [14], that is defined as the angle between perpendiculars drawn to the line of the spine at its inflexion points[3]. One problem that appears when detecting these inflexion points is the presence of noise in the control points when an approximation method is applied[4] in the reconstruction of the curve. So, to solve this problem it is necessary to establish which regions in the curve are candidates to contain an inflexion point.

As a first step, we obtain the straight line that joins both extremes in the spine curve and calculate the distance from each point in the curve to the line, fixing a distance threshold of 7 mm as a criterion of normality for the curve. If the distance is bigger than the threshold, we consider that the curve shows a lateral deviation of the spine. The *lateral asymmetry* is given by the absolute value of the sum of two consecutive angles with opposite sign. In Fig. 2(a), the *lateral asymmetry* in the *front* plane is $20.9°$ in the thoracic region and $13.0°$ in the lumbar region. Other important angle is the *inclination* angle. This angle quantifies the inclination at the end of the curve in the *front* plane. When this angle is small, the mobility of the L5 vertebra with the sacrum bone compensates this deviation, but if it is severe ($>$ 10 degrees), it causes a possible malfunction of the inferior limbs. In the Fig. 2(a), the *inclination* angle is $5.9°$.

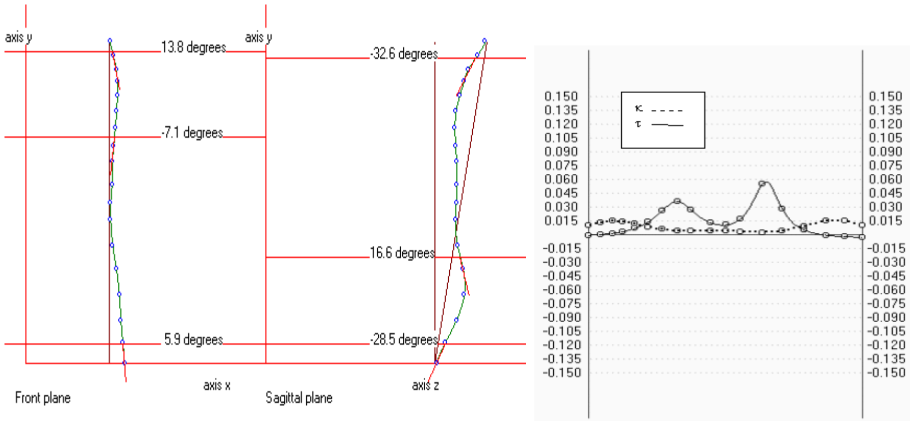
In the *sagittal* plane, the *kyphosis* angle is measured (curve in the upper back zone) and *lordosis* angle (curve in the lower back). For this, the inflexion points are calculated. In Fig. 2(a) the computed *kyphosis* angle was $49.2°$ and the *lordosis* angle $45.1°$.

2.4 Study of the spine curve in 3D

Let be $C(u) : [p_i, p_{i+1}] \rightarrow \Re^3, i = 1...n, u \in [0,1]$ a parameterisation of the spine curve. One problem that affects the computation of the invariant parameters of the curve

[3] Given a 2D discrete curve, we define its inflexion points as those where it presents a change in the sign of the curvature.

[4] We apply a cubic B-spline with C_2 continuity.



(a) (b)

Fig. 2. (a) *Front* and *sagittal* planes of the curve for a patient with a thoraco-lumbar scoliosis with thoracic Cobb angle of 24° and lumbar *Cobb* angle of 12°. In the sagittal plane, a flatten zone appears in the transition of the thoracic region to the lumbar region. (b) The dotted line is the *curvature* κ and the solid one is the *torsion* τ. The two peaks that appear in torsion, imply a high rotation in that region of the curve.

is the existence of errors in the control point positions. So, the curve obtained from the control points must be smooth or the noise of the curvature must be small enough [9, 10]. In our case, we have used a polynomial fitting with regard to the co-ordinates x, y, z and we have computed the coefficients P_x and P_z of the polynomial by least squares, using a threshold in the corresponding correlation index, between the values of the control points and the estimation of the polynomial. The parameterisation of the curve $C(u)$ can be then computer as:

$$C(u) = \left(\sum_{i=0}^{nx} P_x(i)u^i, u, \sum_{i=0}^{nz} P_z(i)u^i \right) \qquad (1)$$

where *nx* and *nz* are the degrees of the polynomials. The two invariant parameters in a 3D curve are *curvature* and *torsion*. They can be calculated from an arbitrary parametric curve through the following expressions that use derivatives of the curve parameterisation:

$$\kappa(u) = \frac{||C' \wedge C''||}{||C'||^3} \quad \text{and} \quad \tau(u) = \frac{det[C', C'', C''']}{||C' \wedge C''||} \qquad (2)$$

A tangent vector **t** can be defined for each point of the spine curve and the plane that is perpendicular to the curve at that point can also be computed, defining, along with **t**, a natural local reference system called *Frenet frame*. The local system vector is given by the following expressions:

$$\mathbf{t} = \frac{C'}{||C'||} \ , \quad \mathbf{b} = \frac{C' \wedge C''}{||C' \wedge C''||} \ , \quad \mathbf{n} = \mathbf{b} \wedge \mathbf{t} \ , \qquad (3)$$

where **b** is the *binormal* vector and **n** is the *normal* vector obtained by a vector product between **b** and **t**. If we consider η and ρ as the angle variations of the vectors **t** and **b**, respectively, we can arrive, by the first order terms of a Taylor expansion, to the following relations for the *curvature* and the *torsion* [6]:

$$\kappa = \frac{\partial \eta}{\partial s} \quad , \quad \tau = \frac{\partial \rho}{\partial s} \tag{4}$$

where s is the arc length. Thus, κ and τ are the angular velocities of **t** and **b**. In this way, the *curvature* gives information about the changes in the orientation of the curve and *torsion* provides information about its rotation. When curves are limited to a plane, the binormal vector is perpendicular to the plane and $\tau = 0$. Through the study of the evolution of κ and τ along the spine curve, we can have a "qualitative description" of how the shape changes affect the properties of the spine curve. With the aim of analysing these variations, Fig. 3 shows a representation of **t**, **b** and **n** in the control points of the curve.

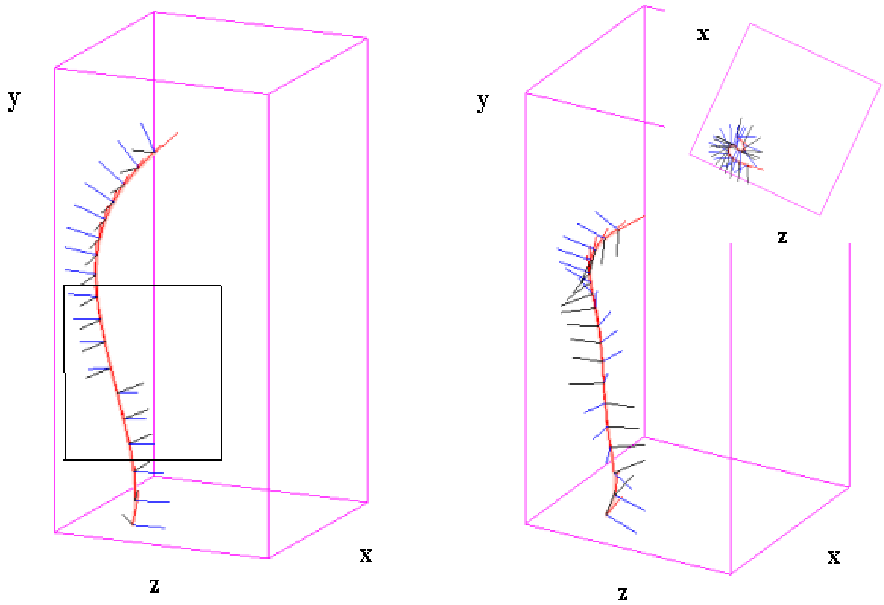


Fig. 3. (Left) A representation of the Frenet frame of a normal spine curve. (Right) Frame evolution for a pathologic spine. In the top-right square, a view from the top is displayed.

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 where the *torsion* has a peak. This implies a change of direction in the vectors **b** and **n** of about 180°, as can be seen in Fig. 3 (left). The *curvature* also maintains this shape of 'S' and the presence of flatten regions indicates the existence of peaks in the *torsion* as can be seen in Fig. 2(b).

3 Experiments and Results

In this study, we have worked with a sample of 76 patients (42 female and 36 male), where a group of 12 patients, aged from 11 to 18 years, had an idiopathic scoliosis process with the following classification: 4 thoracic, 2 thoraco-lumbar, 1 lumbar and 5 double major curves. For all of them, we made a reconstruction of the surface and a specialist fixed the landmarks on the skin at the detected vertebrae.

Table 1. Values obtained for a number of patients for the Ponsetti classification, the *Cobb* angle, *lateral asymmetry* and its *inclination* angles (all measurements are in degrees).

	Thoracic		Lumbar		
Curve classif.	Cobb	Lat.Asym.	Cobb	Lat.Asym.	inclination
Double major	30	32	20	21	7
Thoracic	50	36	–	–	8
Lumbar	–	–	25	26	12
Thoracic	60	50	28	20	7
Double major	30	26	30	26	14
Double major	18	18	15	16	6
Double major	20	20	15	13	6
Double major	35	25	30	21	12
Thoraco-lumbar	24	20	12	13	6
Thoracic	45	27	–	–	–

Some of the studied cases can be observed in the table 1. The spine curve parameters for the thoracic and lumbar regions are displayed both for the *Cobb* angle measured using the classical technique and for the lateral asymmetry extracted through the proposed method. Note that there is a high correlation between the values obtained using both techniques. The correlation index obtained with all the studied cases was $r = 0.89$, being similar to other studies in the literature [4, 14]. This fact supports the diagnostic manually in this measurement.

In the *sagittal* plane, the average value for the *kyphosis* and *lordosis* angles for a group of 30 normal subjects between 12-35 years were 44.5 ± 11.8 and 34.1 ± 10.0 degrees for male and 46.1 ± 11.6 and 39.1 ± 12.6 degrees for female. These values change as a function of age and sex, and allow to establish intervals of normality to detect suspicious cases in the sagittal plane [2].

4 Concluding remarks and further works

We have developed a structured light scheme to obtain a reconstruction of the back function surface. Using this structure, the curve that passes over the main vertebral bodies beneath the skin is obtained, with the aid of a number of landmarks placed on the back surface that indicate the positions of the spinous processes. From these points, a parametric description of the 3D spine curve is computed.

We have measured some characteristic parameters on the projections of the 3D spine curve in the *front* and *sagittal* planes. We get a description of different types of deformities in the spine as a function of the *curvature* and *torsion*, from the evolution of the *Frenet frame* along the spine curve.

We have compared our method to a classical measuring method that uses frontal radiographies to measure the spine deviation and obtained good correlations with it. The information obtained by the classical method requires irradiation of the patient and is subjected to human measuring errors.

In this aspect, this work contributes a development in a project of a classifier that uses the information of 3D geometric invariants from the current classifiers based in the front projection of the curve. On the other hand, the obtaining to a automatic reconstruction method without using the manual placing landmarks is in study.

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