Automatic extraction of the 3D symmetry line of back surface: application on scoliotic adolescents

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***Abstract*— We propose a new method to extract automatically the symmetry line of the 3D back surface of patients affected by scoliosis. Our method is based on the detection of local symmetry planes computed on thick layers of the back. Results have been obtained on a sample of 112 scoliotic adolescents and we compare the symmetry line obtained by our method with a reference line defined by clinicians. We also study the influence of the scoliosis severity and of the Body Mass Index on the results.**

***Index Terms*— Surface symmetry, back surface topography, spinous process line, scoliosis**

I. INTRODUCTION

Scoliosis is characterized by a lateral deviation of the spine in the coronal plane associated to rotation of vertebrae. This abnormal movement of the spine leads to severe impairment of the outer appearance of the back surface. These deformations are generally the basis of a first clinical visual assessment.

Today, the definitive diagnosis and the follow-up are performed by X-ray examinations. However, radiological hazard is a major public health concern. To diminish the number of radiological examinations, many non-invasive methods based on 3D measurements of the back surface using various optical devices (stereophotogrammetry, Moiré fringes, raster-stereography...) have been developed [1]. The challenge of non-invasive acquisition is then the detection of internal deformations of the spine from the back surface.

The symmetry line of the back surface estimates the spinous process line, namely the 3D curve that passes over the main vertebral processes beneath the skin (see the red dotted line in Figure 1, left). Drerup *et al.* [2] showed that this line gives the possibility to evaluate the internal spine morphology.

From a geometric point of view, the back surface can be defined as a bilateral structure that can be divided into two mirrored parts. For healthy subjects, the symmetry plane of the back surface corresponds to the mid-sagittal plane [1] that contains the 3D symmetry line. In the case of scoliotic subjects, the shape of the 3D symmetry line is much more complex. Nevertheless, Di Angelo *et al.* [3] showed that in the presence of pathologies, the spine location can be identified based on a local symmetry property.

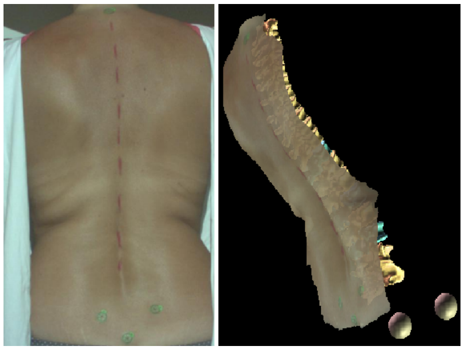

Fig. 1. The spinous process line (in red) passes through the main vertebral processes.

The gold standard for the determination of the symmetry line of the back surface is the "cutaneous" method [4]. It consists in manually marking on the back of the subject the anatomical landmarks corresponding to the vertebral processes and computing their 3D positions. These 3D points are then interpolated in order to construct the 3D symmetry line. However this method, based on very sparse data, is user-dependent and time consuming. This is why research has been focused on automatic and markerless methods that can find a complete line in a fast and reproducible way [5].

In section II, we review automatic methods for computing the symmetry line of the back surface and their limits. In section III, we propose a new automatic robust method that we describe in detail. In section IV, we assess the accuracy and the robustness of the method by comparing it with the reference cutaneous method. A sample of 112 back surfaces of patients, affected by scoliosis, is then analyzed with respect to deformation severity and an anthropometry parameter.

II. RELATED WORK

Many methods have been proposed to detect the symmetry line from a 3D scanned human back surface. We can group them into parallel-section-based methods (see a survey in [5]) and curvature-based methods.

In parallel sections based methods [2], [3], [6], [7], the back surface is sectioned by a set of parallel planes that defines a set of planar profile curves. For each profile, a symmetry point is determined as the minimum of a function, which assesses the asymmetry of the profile. The symmetry line is the result of the interpolation of all these symmetry

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points. An experimental validation [3] evaluates the Mean Deviation Error (MDE) between the reference cutaneous method and the method proposed by [2] and [3] on 75 subjects. This deviation is calculated as the minimal distance between the barycenter of the markers and the symmetry line. The two methods are respectively evaluated to 5.1 mm and 4.2 mm.

Curvature-based methods [8], [9] analyze the topography of the back surface and locate the symmetry line at curvature extrema. The accuracy of the curvature-based method proposed by Poredos *et al.* [8] is evaluated by axial Root Mean Squared Deviation (RMSD) with respect to the reference cutaneous method. RMSD values in the frontal plane in sagittal plane are 5 mm and 1 mm. An other method proposed by Bonnet *et al.* [9] gives an average RMS difference with the reference cutaneous line of 3 mm ± 2 mm on 6 healthy subjects and 1 scoliotic one.

However, automatic methods have some limitations that can be explained by the geometry of the back surface. Some areas, especially at the thoracic level, have salient features that help to find a precise symmetry point in section based methods and to locate curvature extrema in curvature-based methods. These methods are much less accurate when they are applied to areas that are quite flat, especially at the lumbar level. In this case, several minima of asymmetry function or many curvature extrema can be found and the resulting symmetry line can be distorted.

Moreover, we note that the spinous process line is not always located along the back valley. This is certainly due to axial rotation of vertebrae and to balancing muscles. Nevertheless, both section and curvature-based methods are relying on this hypothesis to locate symmetry points or extrema curvatures.

To deal with these problems, we propose to compute symmetry planes instead of sparse points, which could give more accurate results in the case of flat areas or when the spinous process line is not aligned with the back valley.

III. PROPOSED METHOD

A. Overview

Our strategy is to work with thick strips of the back surface and compute their symmetry planes. We define a symmetry plane as a plane that effectively minimizes the difference between a surface and its symmetrical reflection. The set of local symmetry planes determines a patch-wise symmetry surface. Finally, their intersections with the back surface define the symmetry line.

We assume that the back surface is represented by a 3D mesh. To compute the local symmetry planes, we adapted the method described in [10] that determines the parameters of a global symmetry plane of a bilateral point cloud. The global process is shown in Figure 2.

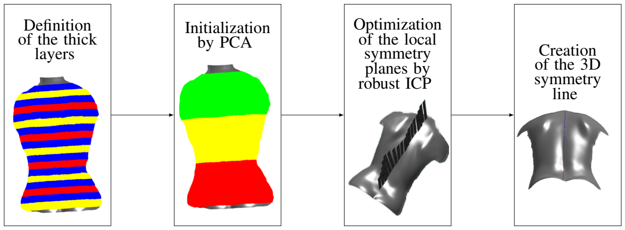

Fig. 2. Overview of the method.

B. Algorithm

Definition of the thick strips: first, the axis of the trunk is defined relatively to the position of two anatomical landmarks that can be easily localized on the back surface: the prominent vertebra and the intergluteal cleft. Perpendicularly to this direction, 18 equidistant thick layers are defined. They correspond roughly to the 18 vertebrae. The intersection between these layers and the back surface results in surface strips S_{i}.

Initialization: we propose to initialize the symmetry planes of the strips S_i by applying a Principal Component Analysis (PCA) on 3 main parts of the back surface.

Parts are defined by grouping 6 surface strips $S_{1 \rightarrow 6}, S_{7 \rightarrow 12}, S_{13 \rightarrow 18}$. For each part, we apply a PCA on the 3D coordinate vectors of the points belonging to the part. PCA gives a new orthogonal frame composed of 3 axes. It is well-known that if a surface is symmetrical, its symmetry plane is orthogonal to a PCA axis [11]. Thereby, we obtain a first estimation of the orientation vector $\mathbf{u_i^0}$ of the symmetry planes of the strips S_{i}.

The distance d_i^0 of the symmetry plane to the origin is set equal to the distance of the centroid of S_i to the origin.

The couple $(\mathbf{u_i^0}, d_i^0)$ gives a first estimation of the symmetry plane Π_i^0 of each strip S_i.

Optimization: as in [10], we propose to use an adaptation of the ICP algorithm to optimize the localization of local symmetry planes. At each iteration, we integrate the TrimmedICP (trICP) algorithm proposed by Chetverikov *et al.* [12] in order to raise the robustness of the method.

Our algorithm follows an iterative scheme that is ran for each strip S_{i}. At iteration j, we have the 3 following steps:

1) The surface of the strip S_i is reflected with respect to the current estimated symmetry plane Π_i^j. Each point $\mathbf{x_k}$ of S_i is paired with the closest reflected point of S_i. This gives a set of registered point couples $(\mathbf{x_k}; \mathbf{y_k^j})$. Notice that for a given $\mathbf{x_k}$, $\mathbf{y_k^j}$ is different at each step as it depends on Π_i^j.

2) The parameters $(\mathbf{u_i^{j+1}}, d_i^{j+1})$ of the new estimation of the symmetry plane of S_i are computed by the two following formulas given in [10]:

$\mathbf{u_i^{j+1}}$ is colinear with the eigenvector corresponding to the smallest eigenvalue of the 3x3 matrix U_{j+1} defined as:

$$U_{j+1} = \sum_{(\mathbf{x_k};\mathbf{y_k^j})} [(\mathbf{x_k} - \mathbf{g_1} + \mathbf{y_k^j} - \mathbf{g_2})(\mathbf{x_k} - \mathbf{g_1} + \mathbf{y_k^j} - \mathbf{g_2})^T - (\mathbf{x_k} - \mathbf{y_k^j})(\mathbf{x_k} - \mathbf{y_k^j})^T] \quad (1)$$

with $\mathbf{g_1} = \frac{1}{N} \sum \mathbf{x_k}$ and $\mathbf{g_2} = \frac{1}{N} \sum \mathbf{y_k^j}$

$$\text{and } d_i^{j+1} = 0.5(\mathbf{g_1} + \mathbf{g_2})^T \mathbf{u_i^{j+1}} \quad (2)$$

3) Iterate if the mean distance between $(\mathbf{x_k}, \mathbf{y_k^j})$ has changed between the last iterations and if a maximal number of iterations has not been reached.

While the standard ICP algorithm assumes that all data points can be paired, trICP rejects outliers and uses only a subpart of the original point cloud.

During step 1, the N_i couples $(\mathbf{x_k}, \mathbf{y_k^j})$ are sorted in increasing order of their distance. At step 2, we select only the first $q_i N_i$ couples of points. The optimal value of q_i is searched during step 1, in a range of $[0.4; 1.0]$, by analyzing the result of an objective function [12].

Creation of the symmetry line: at the end of optimization, we have a local symmetry plane Π_i for each strip S_i (see Figure 3). We can then define the 3 points $\mathbf{P_i^{inf}}$,$\mathbf{P_i^{mid}}$, $\mathbf{P_i^{sup}}$ that are respectively defined at the intersection between the back surface, Π_i and the inferior, midplane and superior plane of the thick layer S_i. All these points are then interpolated by a 3D spline curve in order to form the automatic symmetry line.

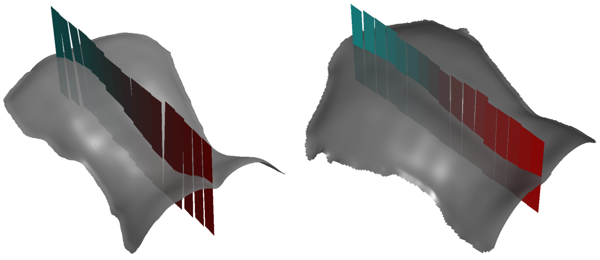

Fig. 3. Automatic detection of the symmetry planes of strips S_i.

IV. EXPERIMENTS AND RESULTS

A. Patient cohort and data acquisition

To evaluate our method, we use data from the clinical study [13] that aims to investigate the correlation between parameters defined on a 3D back surface and on a radiography. 3D back surface of 112 scoliotic adolescents (mean age: 12y) were acquired at the University Hospital of Toulouse (France) by the BIOMOD$^{\text{TM}}$ system[1], which is based on a non-invasive Moiré topography method [14].

Before the acquisition, the clinician marks on the patient's back two anatomical landmarks (the prominent vertebra and the intergluteal cleft) with a red pencil. The more salient processes of the spine are also marked in order to construct the reference cutaneous line (10 to 15 marks are drawn). Marking and acquisition are performed in the same standing posture. After acquisition, the clinician validates the anatomical landmark locations and the cutaneous line on the 3D mesh.

B. Assessment protocol

For each surface, we compute automatically the symmetry line, given only the locations of the two landmarks. In order to compare the cutaneous line C with our automatic symmetry line A (see Figure 4) and to relate these results with other research work, we use the 3 following accuracy indicators.

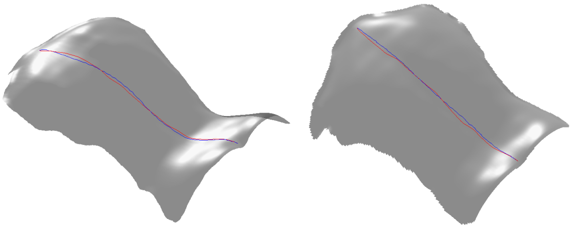

Fig. 4. Comparison between the cutaneous line C (in red) and the automatic symmetry line A (in blue).

The Mean Deviation Error (MDE) is the mean distance between any point of A and the point of C that is at the same height relatively to the trunk axis.

The depth and lateral Root Mean Square Deviations consist in computing the quadratic mean of the distances projected along an axis: anterio-posterior axis for $RMSD_{depth}$ and right-left axis for $RMSD_{lat}$.

Results obtained for the complete sample of patients are given in Table I.

	Number of patients **112 (100%)**
$\mathbf{RMSD_{lat}}$ (mm)	4.82 ±1.81
$\mathbf{RMSD_{depth}}$ (mm)	0.69 ±0.34
MDE (mm)	5.8 ±2.28

TABLE I

COMPARISON BEWTEEN THE CUTANEOUS AND AUTOMATIC SYMMETRY LINES FOR ALL PATIENTS ($mean \pm standarddeviation$).

The severity of scoliosis is evaluated by the Cobb angle, which is measured between the vertebrae at the upper and lower limits of the scoliosis curve [1]. To assess the influence of the pathology on our method, the patient database is divided in 3 subgroups according to the Cobb angle ($< 15°$; $[15°; 25°]$; $> 25°$). For patients affected by double scoliosis, only the highest of the two Cobb angles is taken. Results are displayed in Table II.

	Number of patients / Cobb range		
	22 (24,6%) **[5° - 15°]**	**68 (50,8%)** **[15° - 25°]**	**22 (24,6%)** **[25° - 54°]**
$\mathbf{RMSD_{lat}}$ (mm)	4.54 ±1.90	4.89 ±1.97	4.91 ±1.08
$\mathbf{RMSD_{depth}}$ (mm)	0.58 ±0.33	0.71 ±0.34	0.73 ±0.34
MDE (mm)	5.57 ±2.43	5.89 ±2.44	5.84 ±1.47

TABLE II

INFLUENCE OF THE PATHOLOGY SEVERITY.

A third analysis consists in evaluating the influence of the Body Mass Index (BMI) on the method. The mean value of the BMI is 19, with a range comprised between 14 and 22. This corresponds to representative values for an adolescent population. The patient database is divided in 3 subgroups according to their BMI (< 17 ; $[17 - 19]$; > 19). Results are shown in Table III.

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[1] Acquisition device developed by AXS Medical (DMS Imaging): http://www.dms.com/biomod-3s/

	Number of patients / BMI range		
	42 (37,4%) **[14 - 17]**	**58 (51,8%)** **[17 - 19]**	**12 (10,8%)** **[19 - 22]**
$\mathbf{RMSD_{lat}}$ (mm)	4.88 ±1.71	4.84 ±1.95	4.45±1.36
$\mathbf{RMSD_{depth}}$ (mm)	0.72 ±0.34	0.67 ±0.33	0.74 ±0.36
MDE (mm)	5.91 ±2.28	5.77 ±2.37	5.59 ±1.77

TABLE III

INFLUENCE OF THE BODY MASS INDEX.

C. Discussion

Taking into account the complete sample of patients, the results of the comparison between the cutaneous and our automatic methods show that the mean RMSD is 4.82 mm along the right-left axis and 0.69 mm along the anterio-posterior axis, with a MDE equal to 5.8 mm. These values have to be compared with the margin of error when palpating the midpoint of spinous processes in order to mark the spinous line points. However, manual palpation is not based on accurate reference points [5]. Palpating error was only assessed in the frontal plane and it is evaluated at 9.8 mm, which corresponds to the width of a spinous process [8]. In a general way, we can conclude that results of our automatic spinous process line detection are in the same range as the state-of-the-art methods presented in section II.

The Cobb angle usually correlates with the severity of the scoliosis and the amount of deformation of the back surface. We can see in Table II that the 3 accuracy indicators remain constant with the variations of the Cobb angle. These results seem to show that our method is robust with respect to different back morphologies. This is a major concern in parallel sections based methods as emphasized in [3].

Adolescents with a higher BMI have their back more flattened by the fat layer. This point is very important as high BMI values [8] or flattened conformation [3] can largely influence the symmetry line extraction accuracy in state-of-the-art methods. Nevertheless, our results show no significant changes of the 3 accuracy indicators. This tends to show that our method is robust with respect to morphology variation.

V. CONCLUSION AND FUTURE WORK

In this paper, we propose a new method to compute the symmetry line of the back surface based on local 3D symmetry planes. We show that it gives results that are consistent with the reference cutaneous method. By using a more global approach based on local symmetry planes and not sparse points, we improve the robustness of the method with respect to the disease severity or adolescent morphology.

In the initialization step, two markers - the prominent vertebra and the intergluteal cleft - are required. In order to completely automatize the method, we could detect these anatomical landmarks based only on the surface curvature as proposed by Drerup *et al.* [2] or Bonnet *et al.* [9]. To completely validate the method, we will use frontal and lateral radiographies to correlate our results with the real shape of the spine.

We also plan to extend the method to patients in lateral bending posture. The idea is to adapt iteratively the orientation of the thick strips with respect to the curved trunk axis as proposed in [15].

Lastly, we are going to study correlations between local symmetry planes and clinical parameters in a similar way to the asymmetry analysis conducted by [1].

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