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A computerized method for evaluating scoliotic deformities using elliptical pattern recognition in X-ray spine images

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A R T I C L E I N F O

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A B S T R A C T

Background and Objective: Several studies have evaluated the reproducibility of the Cobb angle for measuring the degree of scoliotic deformities from X-ray spine images, and proposed different geometric models for describing the spinal curvature. The ellipse was shown to be an adequate geometric form, but was not yet applied for the identification and quantification of scoliotic curvatures. The purpose of this study is therefore to propose and validate a novel computerized methodology for the detection of elliptical patterns from X-ray images to evaluate the extent of the underlying scoliotic deformity.
Methods: For anteroposterior each X-ray spine image, the spine curve is first reconstructed from vertebral centroids. The ellipse that best fits to the obtained spine curve is the found within a least square and genetic algorithm optimization framework. The geometric parameters of the resulting best fit ellipse are finally used to define an index that quantifies the spinal curvature.
Results: The proposed methodology was validated on three synthetic images and then successfully applied to 20 clinical anteroposterior X-ray spine images of patients with a different degree of scoliotic deformity, with the resulting maximal relative error of 3% for the synthetic images and an overall error of 0.5 ± 0.4 mm (mean ± standard deviation) for the clinical cases.
Conclusions: The results indicate that the proposed computerized methodology is able to reliably reproduce scoliotic curvatures using the geometric parameters of the underlying ellipses. In comparison to conventional approaches, the proposed methodology potentially produces less errors, requires a relatively low observer interaction, takes into account all vertebrae within the observed scoliotic deformity, and allows for both qualitative and quantitative evaluations that may complement the diagnosis, study and treatment of scoliosis.

1. Introduction

Scoliosis is a medical condition that describes a complex non-physiological deformity of the spine curve in the lateral direction due to muscular or bone anomalies. The deformity is commonly observed on two-dimensional (2D) anteroposterior X-ray images of the corresponding area, and although different methods for measuring the degree of the deformity through the underlying spinal curvature have been proposed [1–3], the Cobb method [4] remains the gold standard for its quantification. The Cobb angle is defined between the two straight lines that are tangent to the superior and inferior endplate of the, respectively, superior and inferior end vertebra of the deformity, and angles above 10° describe scoliotic curvatures. Several studies tested the reproducibility and reliability of the Cobb method in measuring the severity of both idiopathic and congenital scoliosis [1], however, only few studies [3] focused on methods that make use of sophisticated computerized image processing combined with pattern recognition techniques. As a result, several studies reported errors of up to 10° when using the Cobb method [1,2,5], which is related to the fact that it describes changes in the inclination of the end vertebrae rather than changes in the spinal curvature, and that it neglects the translation of the apical vertebra of the scoliotic deformity. Such a level of uncertainty makes follow-up examinations and the identification of a possible progression of the deformity inaccurate, and may, in the worst case, induce the healthcare professional to recommend, al-

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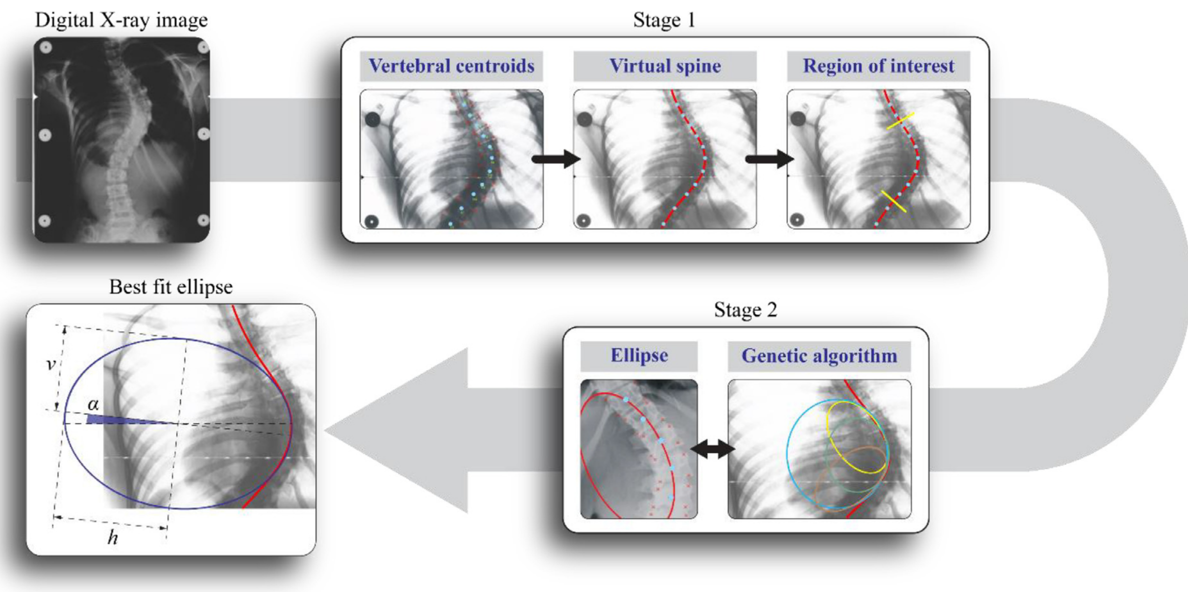

Fig. 1. Summary of the proposed computerized method for modeling the scoliotic spine curves with ellipses.

though not necessary, more intensive treatments (*e.g.* orthopedic corsets, surgery).

Although the decision for treatment has to take into account other important factors, for example, the patient development, condition, and to which degree the deformity has compromised the respiratory flows, it is also important to propose and develop *complementary* methods that aid in the analysis of scoliotic deformities with a good degree of reliability. Several studies have focused on methods based on different geometric models for describing the spinal curvature [1,6], and the results show that the ellipse may be an adequate geometric form [5,7,8] for representing kyphotic and lordotic spinal curvatures in lateral 2D images, but was not yet applied for the identification and quantification of scoliotic curvatures. The objective of this work is therefore to develop a novel computerized methodology for analyzing anteroposterior X-ray spine images to obtain ellipses that model the geometric form of the imaged scoliotic spines and allow for a global evaluation of the entire scoliotic curvature. The proposed methodology has the advantage of requiring low observer interaction, takes into account almost all the vertebrae within the deformity, and allows for both qualitative and quantitative evaluations. In addition, the parameters of the obtained ellipses can be also used to define an index for quantifying spinal curvatures.

2. Methods

By considering the input in the form of an anteroposterior 2D X-ray image of a scoliotic spine, the proposed methodology returns the parameters of the ellipse that models the scoliotic spine curve. The methodology can be divided into two stages that are summarized in Fig. 1. In the first stage, the basic spine curve is reconstructed from the centers of the vertebral bodies, and the starting and termination points of the scoliotic curvature are identified. In the second stage, an ellipse is fitted to the scoliotic curvature using the least squares (LS) and genetic algorithm (GA) for optimization.

2.1. Reconstruction of the virtual spine

In the anteroposterior 2D X-ray spine image, the user first identifies the four corners of each vertebral body. The center point of each vertebral body, *i.e.* the vertebral centroid, is then defined [9] at the intersection of the lines traced diagonally from the identified corners (Fig. 2(a)), and represent the initial shape of the spine curve. From the coordinates of a total of M' vertebral centroids, a curve denoted as the *virtual spine* is reconstructed [10] by polynomial interpolation, resulting in N' ; $N' >> M'$ points that interlink smoothly the adjacent vertebral centroids, and represent a more detailed shape of the spine curve (Fig. 2(b)). The starting and termination points of the scoliotic deformity (Fig. 2(c)) are then identified at the locations of the most inclined vertebrae on, respectively, the superior and inferior half of the virtual spine by applying numerical derivation for evaluating the inclination among vertebrae [11], resulting in the region of interest of N; $N < N'$ points along the virtual spine that encompasses M; $M < M'$ vertebral centroids.

Basically, the extraction of endplates used here and adapted from [11] uses the four corners of each vertebral body (identified by the user) to define superior and inferior end vertebrae's (Fig. 2(c)). Then, this definition is done by the inclination of horizontal endplates of the vertebrae's as represented in Fig. 2(d). In sequence, the first order differentiation of the slope is applied and the zero crossing sequence represents the (i) superior end vertebra, (ii) the apical vertebral and (iii) the inferior vertebra as represented in Fig. 2(d).

2.2. Modeling of the spinal curvature with an ellipse

Once the basic geometric form of the spine is reconstructed and represented in the form of the virtual spine, the next stage is to find the ellipse that best fits into this geometric form. For this purpose, the LS numerical optimization method is initially used and constrained by specific mathematical conditions, and then combined with the GA to reduce the effects of local minima. In geometry, ellipses are planar curves that result from the intersection of a cone by a plane, and represent the closed type of a conic. The general equation of a conic is given by:

$$ax^2 + bxy + cy^2 + dx + ey + f = 0, \quad (1)$$

where x and y represent, respectively, the horizontal and vertical coordinates of a point in the image forming a column vector $\mathbf{x} = [x^2, xy, y^2, x, y, 1]^T$, and row vector $\mathbf{p} = [a, b, c, d, e, f]$ represents the real-valued parameters of the conic (with a, b and c not