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Spinal Curvature Determination from an X-Ray Image Using a Deformable Model

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Abstract- **This paper presents a spinal curvature determination from frontal X-ray images of scoliotic patients. A new deformable model, Modified CPM (Charged Particles Model), has been developed and used to determine the spinal curvature. The Modified CPM is a new approach of a deformable model based on CPM, which was introduced in 2004. The X-ray image is charged negatively according to the edge-map or gradient-magnitude image. The particles are attracted towards the contour of the object of interest, because this contour is very dark, thus charged very negatively. We modified the CPM by putting springs between the particles to prevent the particles from moving away and keep the movement of the particles in the appropriate distance without reducing the flexibility to follow the curvature. The results of the implementation show the effectiveness of the modified charged-particle model for spinal curvature determination on X-ray images.**

I. INTRODUCTION

Scoliosis is a three-dimensional deformity of the spinal column. It is generally characterized by a lateral deviation of the spine, accompanied with an axial rotation of the vertebrae. The standard radiology evaluation of adolescent idiophatic scoliosis consists of standing antero-posterior and lateral radiograph of the full spine. The Cobb method is used to measure the curvature of spinal column on the AP (antero-posterior) film and determines the severity of the scoliosis. Usually the physician calculates the Cobb angle manually on the AP film or by drawing 2 lines from the digital image using mouse and computer will calculate the angle between those lines.

The radiographic measurements by putting six landmarks manually per vertebra on each AP radiograph were done by Wever *et. al*. [2]. These landmarks were scanned and saved as Cartesian coordinates in a computer file. He calculated the midpoint of the vertebral bodies and the lateral tilt of the upper and lower end plates of each vertebra by a computer algorithm. The Cobb angle consisted of the angle between the upper endplate of the upper, most tilted vertebra and the lower endplate of the lowest, most tilted vertebra in the scoliotic curve.

A comparison of manual versus computer-assisted radiographic measurement of Cobb angle (performed on digitized images using a computer mouse) was done by Shea *et. al.* [3] in 1998. By using these computer technique sources of intrinsic error, e.g., the variability introduced by using different manual protractors, the inaccuracy of standard protractors, and the use of wide-diameter radiographic markers, were avoided. However, determining the upper and lower vertebra still has to be done manually and can cause an intrinsic error.

To further automate curvature determination will be a great contribution for this problem. We propose the use of deformable models, more specifically a tailored version of the Charged-Particles Model to determine the curvature automatically.

Deformable models were first introduced by Terzopoulous *et al.* [4] in 1998. A survey of deformable models in medical image analysis has been performed by McInerney *et al.* [5]. Deformable models are curves, surfaces or particles defined within an image domain that can move under the influence of *internal forces* and *external forces*. Internal forces are defined within the curve, surface or particle and external forces are computed based on the image data.

A different approach of the deformable model is based on the use of charged-particles. The Charged-Particle Model (CPM) was first introduced by Jalba *et al.* [1]. This model is inspired by classical electrodynamics and is based on a simulation of charged particles moving in an electric field. The particles have a positive charge and move freely in an external electrostatic field $\bar{E}$, generated by fixed, negative charges, placed at each pixel position of the input image, with a charge magnitude proportional to the edge-map of the input image.

The important characteristics of the CPM are lower sensitivity to initialization, better capture range and convergence into boundary concavity [1]. However, the

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particles can move apart if the inter-particle force is too high or the distance is too small. Other disadvantages of CPM are the difficulty to maintain any structure in the distribution of the particles, or defining some shape prior. These problems become severe in the presence of many cluttered features, as in the case of our X-rays.

In this paper we introduce a new method based on the inclusion of springs in the CPM. The charges are attracted toward the contour of the object of interest by a negative electric field. The springs prevent the particles from moving apart and keep the movement of the particles at appropriate distances without reducing the flexibility to follow the curvature.

This paper will describe the feasibility of a modified charged-particle model to determine the spinal curvature from an X-ray image.

II. Materials and Methods

1. Frontal X-ray images

50 Frontal X-ray images of scoliotic patients were used, both single and double curved. The acquisition of a series images was done on a Philips Multidiagnost Radiofluoroscopy system and the reconstruction process which combines the different parts of the spine was done by the Philips Easy Vision system, Radiology Department, University Medical Center Groningen, The Netherlands.

2. Image Pre-processing

Six groups of morphological image pre-processing methods, namely top-hat filtering (TH) and five modified top-hat filtering (ModTH-1 – ModTH-5) methods were studied to improve the quality of the X-ray images, especially to eliminate an uneven background, which usually appears on X-ray images and to boost the thoracic part which is less visible due to over projection of the sternum. The modified top-hat filtering method is based on eq.1.

$$f_{ModTH} = \frac{(f \bullet b_n) - f}{f \bullet b_n}\gamma \qquad (1)$$

where f_{ModTH} is modified dark top-hat filtering, '$\bullet$' is closing of morphological operator, b_n is a structural element and γ is an attenuation factor. For every modified top-hat filtering method, five different sizes of structural element (disk1-disk5) and five different attenuation factors were used to evaluate 50 frontal images. The positions of the particles of 31 images for every frontal image, before and after preprocessing, are evaluated visually. This resulted in the evaluation of more than 1500 images. For each image we recorded whether the particles fit the curvature or not.

3. Curvature determination

The curvature determination was done by Modified CPM. This method simulates the behaviour of positively charged particles moving in a simulated electric field derived from the grey level image. This electric field has a charge magnitude proportional to the edge-map of the input image.

The modified CPM is formulated based on (2), so the resulting force $\vec{F}$ acting on every particle is:

$$\vec{F}(\vec{r}_i) = \vec{F}_c(\vec{r}_i) + \vec{F}_l(\vec{r}_i) + \vec{F}_s(\vec{r}_i) - \beta\vec{v}_i \qquad (2)$$

where $\vec{F}_c$, $\vec{F}_l$, $\vec{F}_s$ and $\beta\vec{v}_i$ are the Coulomb force, Lorentz force, Spring force and damping or viscous factor. The particles that are charged positively, are attracted towards the curvature of the image, because this contour is very dark, thus charged very negatively.

The Coulomb force $\vec{F}_c$ acting on a particle p_i with charge q_i is the sum of all Coulomb forces generated by all other free particles and given by:

$$\vec{F}_c(\vec{r}_i) = q_i \sum_{j \neq i}^{N} \frac{q_j}{4\pi\varepsilon_o} \frac{\vec{r}_i - \vec{r}_j}{|\vec{r}_i - \vec{r}_j|^3} \qquad (3)$$

The Lorentz force $\vec{F}_l$ acting on particle p_i with charge q_i is given by

$$\vec{F}_l(\vec{r}_i) = q_i\left(\vec{E}(\vec{r}_i) + \frac{\vec{v}_i}{c} \times \vec{B}(\vec{r}_i)\right) \qquad (4)$$

where v_i, c, $\vec{E}(\vec{r}_i)$ and $\vec{B}(\vec{r}_i)$ are the speed of the particle, the speed of light, electric field and the magnetic field. Since a magnetic field is absent ($\vec{B} = 0$), and the Lorentz force becomes

$$\vec{F}_l(\vec{r}_i) = q_i\vec{E}(\vec{r}_i) \qquad (5)$$

with a direction parallel to that of the electric field $\vec{E}$. The magnetic field generated by the moving particles is ignored.

A spring is put between two particles and the spring force is calculated in every particle. A spring is characterized by Hooke's law.

$$\vec{F} = -kd\vec{X} \qquad (6)$$

where k is the spring stiffness and $d\vec{X}$ is the spring deflection from the undeflected position, caused by a force $\vec{F}$.

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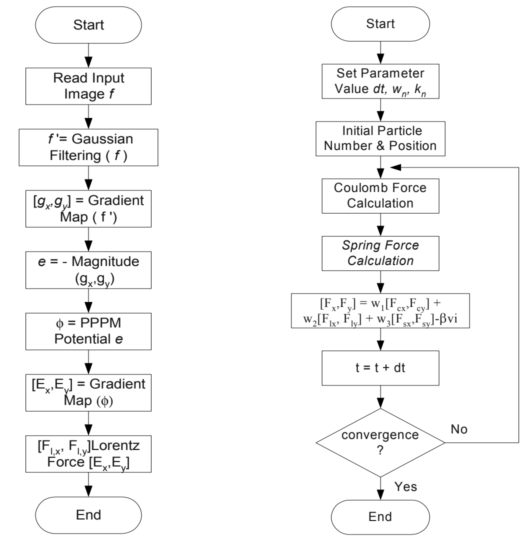


Fig.1 Flowchart for the external field (Lorentz Force) and movement of particles

The springs prevent the particles from moving away and restrict the movement of the particles without reducing the flexibility to follow the curvature

The algorithm of this method consists of two parts, the calculation of the electric field from a postero-anterior X-ray image and the computation of the particle dynamics. Fig. 1 shows the flowchart of modified CPM algorithms.

The algorithm is based on the CPM algorithm [1], but we insert the spring force calculation in the total force calculation of the particle dynamics for every particle. First step in the computation of the external force, Lorentz force, is image filtering using Gaussian filtering. The gradient map from the result of Gaussian filtering and the magnitude of the gradient map are computed and passed as input to the Particle-particle particle mesh (PPPM) method from molecular dynamics [9]. Finally, the external field or Lorentz force is created from the gradient map [E_x, E_y]. The second part of the algorithm concerns the movement of particles based on the Coulomb and spring force, shown as flowchart in Fig. 1 (right). We define the number and the initial position of the particles. Then, the Coulomb force and spring force are calculated and the particles will move until convergence.

III. RESULTS

1. Image pre-processing

50 Frontal images of scoliotic patients have been improved by pre-processing using top-hat filtering or a modified top-hat filtering method. Fig. 2 shows the results of curvature detection after the different types of filters were applied. The filters are modified top-hat filters using different size of structural elements and different attenuation factors (group 2 – group 6, left bar). The type of the structural elements is ‘disk’.

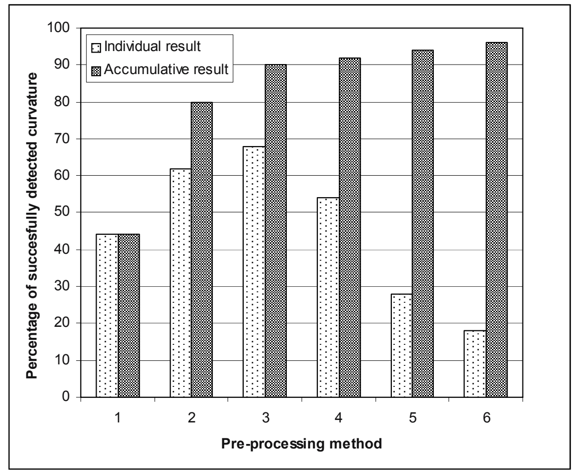
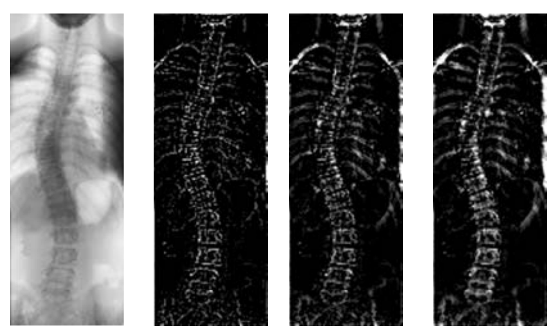


Fig. 2 The result of curvature detection using 6 different groups of image pre-processing, left bar: the individual result- right bar: accumulative result. (1) Without pre-processing, (2) Top-hat filtering, (2-6) Modified top-hat with different structural disc element and different attenuator factor.

Fig. 3 shows an example of an original image and the resulting image after enhancement using the modified top hat filtering method with 3 different attenuator factors.



(a) (b) (c) (d)

Fig. 3 (a) The original image and (b), (c), (d) the images after the enhancement result by using modified top-hat filtering with 3 different attenuator factors.

2. Curvature determination using modified CPM

The modified CPM is applied to determine the spinal curvature from an X-ray. 2 reference points were placed at top and bottom. For several images which have more complicated curvature, 3 or 4 reference points are needed. Only the first and last reference points will be fixed on that position.

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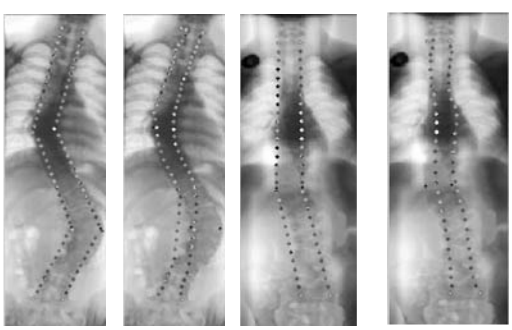
The curvature of 22 frontal original images (44%) was detected without image pre-processing. By applying different image pre-processing method 96% of the spinal curvature can be determined.

By using this method, the physician must accept or reject the result. If the result is rejected, then he/she can continue using the image pre-processing to get better result. Fig. 4 shows the result of the modified CPM on an X-ray image of a scoliotic patient.

Fig. 5 shows the failed result of the implementation of modified CPM on X-ray image curvature determination caused by unclear vertebra structure or the spinal curvature too close to the boundary of image. Some cluttered features, such as ribs, also cause the particles to move from the spinal curvature. This problem can be solved by putting fixed reference points in certain places, so the particles will be in the proper position.

(a) (b) (c) (d)

Fig.4 The modified CPM applied on an X-ray image of a scoliotic patient. (a) Original Image, (b) Initial particles position, (c) Particles attached the curvature, (d) Final particles position



(a) (b) (c) (d)

Fig. 5 Failed result of the implementation of modified CPM on X-ray image curvature determination. (a) (b) Initial position and final result of frontal 4, (c) (d) Initial position and final result of frontal 18

IV. Discussion

The determination of the spinal shape is very important for the orthopaedic surgeon to evaluate curve progression especially for severe cases of scoliosis (Cobb angle greater than 45 degrees). Spinal curvature determination and Cobb angle measurement is the most important step before we can determine the spinal shape. For this purpose, modified CPM could give a contribution to determine the curvature and Cobb angle measurement.

The result of detecting the spinal curvature on an X-ray image with an artifact in the thoracic area shows that the combination of spring and CPM can detect the spinal curvature very well. A more detailed investigation shows that a technical improvement of spring forces in the CPM method with different configuration (closed spring curve and its combinations) can be adapted for general applications and specific applications by using appropriate spring-particle configuration.

Detecting the spinal curvature only failed totally in two of the fifty images because the position of some vertebrae was very close to the image boundary. To overcome this problem, a marker is needed to be given in a certain area to increase the negative field. The other frontal X-ray images of scoliotic patients can be detected when one of the proposed image pre-processing methods is applied.

V. Conclusions

With the modified CPM the global curve of a spinal X-ray image of a scoliotic patient can be determined, even though there are many cluttered features. The modified CPM can also be used to determine both open curves and closed curves without collapse. Other shape priors could also be generated. The modified top-hat filtering gives very good results based on the number of detected curvatures.

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