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Diagnostic moiré image evaluation in spinal deformities

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This paper deals with moiré picture evaluation in case of a very frequent spinal deformity, called the Scheuermann's disease. Spinal deformities often occur in the group of 10–17 year-old children. This Scheuermann-type of spinal deformity is more frequent (11%) than the well-known scoliosis (2–4%), but because of the incorrect diagnosis it often remains without a right treatment. Now the accepted medical diagnostic method is using frontal and lateral X-ray pictures from patients' back. Our already presented method uses moiré pictures to establish the right diagnosis. This optical method is fast, non-contact and arbitrarily repeatable. In our former paper we presented two computer algorithms to produce the shape of the patients' spine. These methods showed good agreement with the traditional medical diagnosis, but the extreme search method returned better results. In this paper we are demonstrating our new results using the extreme search method and the improved computer program.

Keywords: moiré method, image processing, Scheuermann's disease, curve determination.

1. Introduction

The issue of investigation of the spine and spinal deformities are among current research topics. Researchers often deal with the better known and easier diagnosed scoliosis [1]. RUEY-MO LIN and co-workers [2] used lateral radiographs – like us in our former paper [3], but they examined the changes of lumbosacral lordosis in case of adults. Diagnostic picture analysis is also a popular research topic. MING-SHIUM HSIEH and co-workers analyzed 3D images of spinal fracture diagnosis [4]. They used radial diagnostic image records that can be harmful for patients, mostly for children. That's why the application of non-contact optical methods become more common, just in case of the moiré method. These safe measurement methods can replace the traditional solutions [5]. The geometric interference-based moiré method is a useful tool in orthopedic protocol to identify the majority of types of often occurring spine deformities [6]. Scheuermann's disease is significant among other spine diseases, but the development

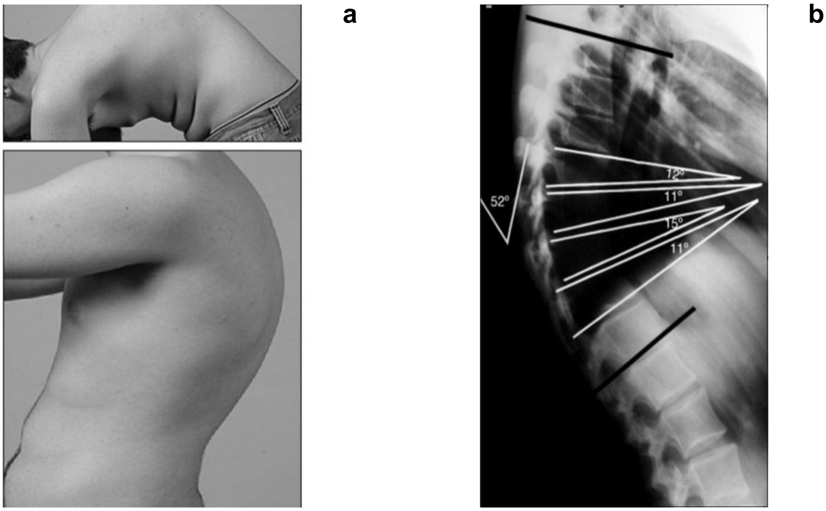

Fig. 1. Round kyphosis of a Scheuermann's disease patient (**a**). X-ray picture of a Scheuermann's disease spine (**b**) [17].

of identification methods is out of the researchers' interest. This special type of spinal disease was described in 1920 [7], the overall level of the roundback in the upper spine part is increased (Fig. 1). The importance of the diagnosis and treatment of Scheuermann's disease in orthopedic practice is increasing.

Recognition and restitution of free form surfaces are important in computer aided measurements. These techniques are used in industrial quality control of manufactured components, object identification and orthopedic supervision [8–10]. Structured light, moiré and interferometric are the well-known methods used for optical measurements [5]. They are based on non-contact procedures and have different working ranges and sensitivities [11].

Automatic control systems can also consist of moiré topographical methods, because mechanical solutions often cannot be implemented in measurements. In case of robotized manufacture for qualification, controlling disposition and size accuracy of products, these methods are also suitable [12].

From the above described techniques, the moiré method is a time-honored technology and can be applied for the examination of symmetry and height differences [13]. It is often used in plastic surgery and orthopedics [14].

So far moiré photographs were only used for subjective comparison [15], but in our former study a computer program was developed for determination of spinal deformities and it followed the condition of patients [11, 15, 16]. Using this program, a spine line is produced that fits well the real shape of the spine. From this spine line, the traditional Cobb angle is measured and compared to the Cobb angles originated from orthopedists. One of the important innovations in our recent study is the automation of Cobb angle measurement. This development verified our results and accelerated the evaluation.

2. Spinal deformities

There are two huge types of spinal deformities, which are scoliosis and Scheuermann's disease. In this paper we introduce the characteristics of these spinal deformities.

In case of scoliosis, the spine is crooked in the frontal plane, and vertebrae are rotated many times along the spine. Contrarily, in case of the Scheuermann's disease, the spine is straight in the frontal plane, problems are visible exclusively from the sagittal plane. The upper side of the spine, the kyphotic part, is more rounded than at healthy people. Unfortunately, frequently the grade of this deformation is not measured and the diagnosis is recognized as a simple negligent pose. Without a right treatment – physiotherapy and wearing a Gschwend type brace – the deformation remains until the end of the patients' life. Lumbar kyphosis is also very frequent. In this type of disease, the spine is straightened on the lumbar part and causes a flat back. Compared to the scoliosis, the diagnosis of Scheuermann's disease is more difficult because scoliotic curvatures and rib humps are visible on the patients' back even without a diagnostic imaging test.

Without X-ray a simple physiotherapist test – named Adams test – must be performed, where patients only have to bend forward with outstretched arms. If the kyphotic hump cannot disappear in this bended position, Scheuermann's disease is diagnosed.

Using the traditional diagnostic method, the main evidence of this disease is the changed shapes of vertebrae on the concerned section. If at least three consecutive vertebrae are lower on the inner part of the spine, the disease is diagnosed. In this concerned section, the collagen combination changed in the endplates of vertebrae and the cartilage rift was narrowed as well. Also, according to the traditional diagnostic method, the Cobb angle is measured on plane radiographs by drawing a line through the superior endplate of the superior end vertebra of the scoliotic/pernicious kyphotic curve, and another line through the inferior endplate of the inferior most vertebra of the same scoliotic/pernicious kyphotic curve, then by measuring the angle between these lines [18]. This method can be used in case of scoliosis and Scheuermann's disease as well.

Using our innovative method, we are trying to replace the time-consuming and risky diagnosis with an easy, safe and fast solution that provides correct results.

3. Moiré effect

The moiré phenomenon arises as the result of the interaction of two periodic structures [19]. It is observed as a space modulated intensity pattern consisting of dark and bright stripes. The moiré pattern is a system of the bright stripes that are called moiré fringes [20]. It means that the moiré stripe is the manifestation of the moiré phenomenon. The moiré-based representation of the measured or tested surface is similar to the contour lines of the maps but described in a more general form. The moiré lines connect the points of a surface with a constant distance from the reference plane which distance depends on the parameters of the layout geometry.

3.1. Measurement by moiré equipment

By processing of commonly used images, the moiré effect is undesirable, as it can be known from the theory of periodic and aperiodic interaction of layers. Certain sorts of anti-moiré and anti-aliasing algorithms are used to eliminate the disturbing moiré effect that arises from the superimposing of different structures. In spite of this fact, the moiré effect has useful technical applications. The moiré fringe-based shape detection is a frequently used tool to solve nonconventional measurement tasks. The moiré effect occurs with two periodic and overlaid structures in case of its interaction. In this sense, the spacing and orientation of the moiré fringes depend on the spacing and orientation of the base structures. Description and behavior investigation of the phenomenon based on widely published geometric methods can be applied [21]. After the preprocessing of moiré patterns, the main step is the fringe order determination in all cases. This is possible by fringe phase extraction methods. Information of the measuring physical quantity can be obtained after analyzing the phase of the moiré fringe patterns using the geometric parameters of the applied equipment.

3.2. Base arrangements

To generate moiré patterns, two gratings characterized by the spatial frequency are necessary. The phenomenon is a result of superimposition of a specimen and master grating. In most cases, these gratings are parallel-equidistant and characterized by the spatial frequency specified by the number of lines per unit length. Moiré fringes generated by shadow moiré arrangement are contour lines of equal depth. In this type of equipment, patterns are generated by superimposing a physical grid and its shadow projected on the examined surface positioned in front of the illuminated grating. The shadow of the grating is projected on the surface of the specimen (Fig. 2**a**) [22].

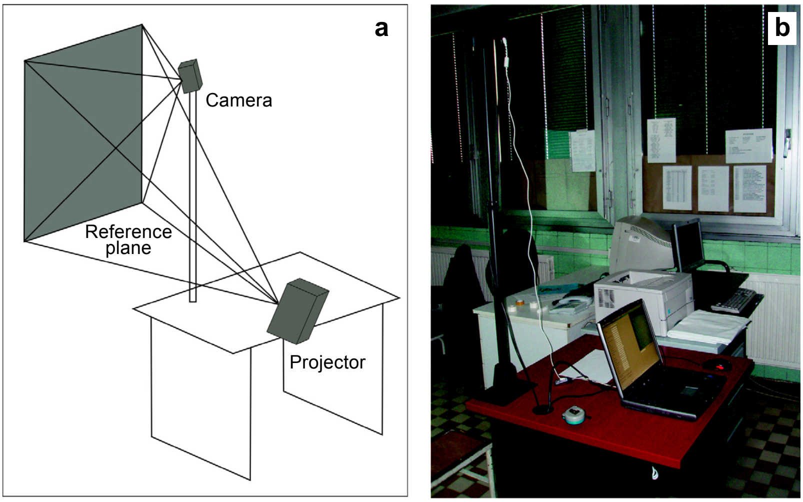

Fig. 2. Optical layout of the electronic moiré equipment (**a**). Operating equipment (**b**).

In the projection, moiré equipment surface contouring is created with another method. Reference grating is projected onto the examined specimen using an optical system (Fig. 2**b**). This deformed grid is observed through a reference grating. Both equipment produce a system of moiré fringes describing constant out-of-plane depth. Surface height is measured relative to the reference surface. The depth resolution is the function of spatial frequency of gratings and geometry of the equipment. A significant advantage of the projection moiré equipment is the use of the second grating. Its spatial frequency control allows continuous and flexible change of the measurement resolution and modifies the reference plane position [23]. In practical applications the use of projection moiré is more frequent because the degree of binding is lower between the phenomenon and the observing grating [14].

3.3. The electronic moiré equipment

The measurement can be also performed without physical creation of moiré patterns. There is a possibility of pattern creation using electronic projection moiré equipment during a computation process in the memory of the computer. Both of the projected and the master gratings are electronically generated. The moiré patterns are created using this virtual reference grating and the captured object grating in the memory of the computer. In this way the complete independence of both gratings is guaranteed in amplitude and phase [5]. Important attribution of the electronic moiré equipment is the possibility of a flexible follow-up adjustment by processing the measured data.

4. Processing of moiré images

At first the main steps of our evaluating method are summarized, then the innovation and development of the program is presented.

As described above, the electronically generated moiré pictures are appropriate to determine the Scheuermann's disease. A software was developed in LabVIEW programming environment to identify the level of this disease-type. The user-friendly interface of the software allows the greater traceability, simple and flexible application and variation of implemented algorithms.

The default moiré picture processing algorithm is implemented in the following steps:

1. Moiré picture is edited according to the examined part of the back. Two markers were glued on the back during measurement to get the right location of the cervical 7th (C7) and lumbar 5th (L5) vertebrae. These are the basics for the fitting method.
2. Preparation of the acquired moiré picture for processing by execution of the image processing algorithms and by generation of an auxiliary mesh layer (Fig. 3**a**).
3. Cholesky algorithm-based generation of an n-th order fitting curve. The polynomial is based on intersection points of the horizontal mesh lines of the moiré fringes (Fig. 3**b**).
4. Application of the algorithm based on inflection point identification. There are two generated tangents to the approximated curve in inflection points. The intersection

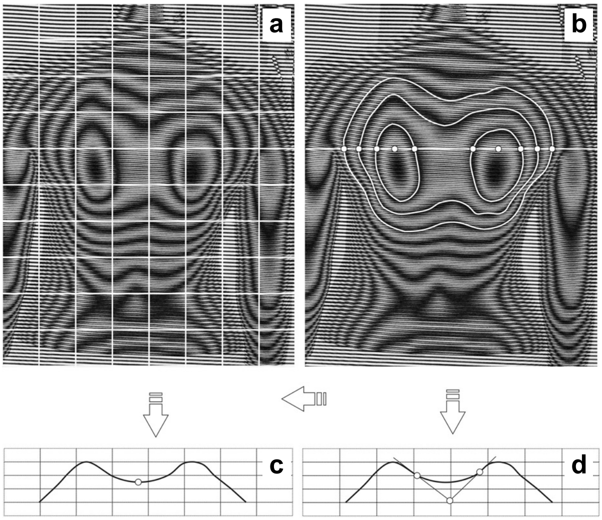

Fig. 3. Steps of the moiré picture processing algorithm (see text for explanation).

of tangents gives a point of the spine in one possible sagittal plane (Fig. 3**c**). Note that the selected inflection points have to locate in the valley of the back.

5. Application of the algorithm based on the extremes of the fitted polynomial. The calculated extreme of the fitted curve located in the valley of the back gives a point of the spine (Fig. 3**d**).

6. The final possible shape of the spine is obtained by executing one of the before mentioned algorithms on every horizontal lines of the mesh.

7. Application of the traditional method based on computerized calculation to obtain the Cobb angle of the spinal curve.

The level of interaction of this software was intermediate. This enabled a modification of execution in the process or in the algorithms by the user. The preparation of the acquired moiré picture was manual. Color conversion, luminance extraction, trans-

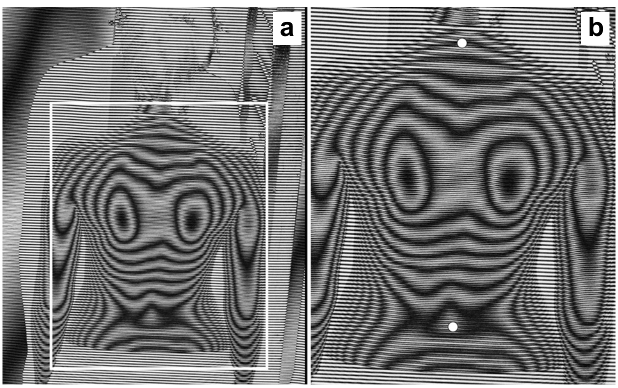

Fig. 4. The important parts of the moiré picture (**a**). Two markers for the fitting method (**b**).

formation to the grayscale model was executed independently. The selection of the region of interest (ROI) was manual (Fig. 4**a**) depending on the base settings of the original moiré picture. It is possible to adjust the main direction of the image by rotation, if required. Very important are gluing markers (Fig. 4**b**) indicating the starting and ending points of the determined curve of the spine. Our experiments confirmed that the real biological shape of the spine can be described by 3rd order polynomial.

5. Innovations of the evaluating program

The first modifications were the automation of an auxiliary mesh layer generation and the check mark of intersection points. A median filter with given pixel width is applied along the contour line. A selected border is adjusted and the pixels above this border are marked by the program along the grids. So the intersections can be found more precisely. This development could greatly speed the length of the evaluation.

The other innovation was the automation of the Cobb angle measurement. Before this, a traditional technique (manual measurement) was used presenting the Cobb angles, which was not accurate enough. Because of the inaccuracy of drawing, the margin was only 5 degrees. Now using the automatic method, the margin is less than 1 degree, so our results are in better agreement with the original outcomes.

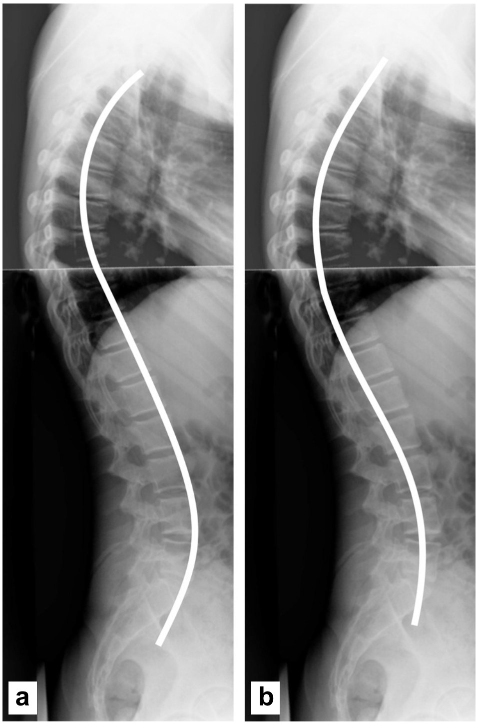

Fig. 5. The generated spine line using the minimum point method (**a**). Generated spine line using the extreme search method (**b**).

This automation technique now uses the lateral X-ray pictures of patients because of the supervision (Fig. 5). The next step of development is going to be the totally automatic Cobb angle measurement. The current function of this Cobb measurement starts with the exact fitting of the X-ray picture and the generated spine line using the glued markers. These help fitting the generated line that matches well to the original spine. These markers are glued on the patients' back during taking the moiré picture. The next step is marking the two endpoints of the morbid kyphotic curve, near the appropriate intervertebral gap. Then the program draws a tangential to this chosen point and produces a line perpendicular to this tangential. These steps are performed in the start and endpoints of the morbid curve, and the program measures the angle next to the intersection point of these lines. This measurement method is equal to the drawing of medically originated Cobb angles, so these values must be correlated in case of a right operation.

6. Results

In this study, additional 54 moiré pictures were evaluated. In some cases the results of measurements are matching, that's why less measurement points can be seen in Fig. 6. According to our former results [3], in this study only the extreme search method was used because it showed more precise results than the inflexion point searching method. Results were compared statistically to the outcomes of the traditional evaluation.

By statistical analysis, the traditional results and our current results formed two groups. These were examined paired and unpaired as well.

The first analysis was the D'Agostino–Pearson omnibus normality test. Values of both groups follow the normal distribution, so a bell curve can be fitted on the histogram of the test results.

The mean value of the medically originated Cobb angles group is 48.06, while the mean of the extreme search method group result is 43.80. The standard deviation of the first group is 4.063, in case of the second group 4.173. The values of standard errors are close, in the group of traditional Cobb angles it is 0.5678, in the other case 0.5529.

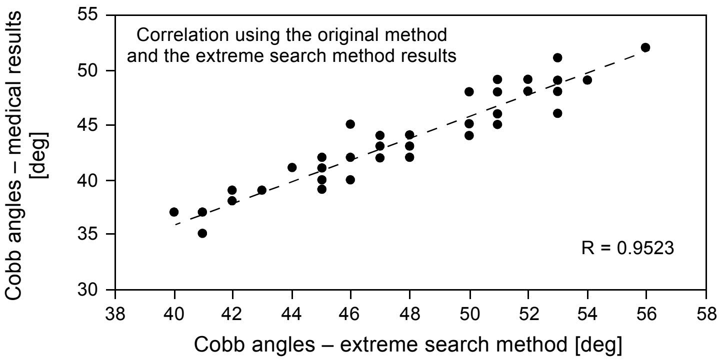

Fig. 6. Correlation results.

The groups were examined using the paired and unpaired type of t-tests. The unpaired t-test gave a positive result – the p value is less than 0.0001 – so the groups are significantly different. Using the paired t-test, the accomplishment is the same, and pairing was effective according to the correlation coefficient.

The value of the correlation coefficient is 0.9523, this match is clearly visible (see Fig. 6).

7. Discussion

Our research is important and up-to-date, because nearly 11% of children suffer from Scheuermann's disease opposite to the case of scoliosis (2–4%).

In this study our former results have been approved, as current outcomes gave us similar good results, to our first examination. According to these results, this method and the developed program shall be considered appropriate for diagnosing Scheuermann's disease. The lateral shape of the spine was successfully produced from the moiré pictures taken in the frontal plane. The extreme search method invented by us is capable for producing the spine line without harmful radiation.

In this diagnostic method, harmful radiation does not impair patients' bodies, that's why it can be repeated any number of times. Because of the non-contact nature, the positions of points of patients' back can be observed at the same time. The movement of children's bodies can be often obstructive in other examinations, for example, using a spinal mouse or other body used orthopedic measurement techniques.

The software operates well but for the final utilization a few ameliorations are indispensable. Measurement of the Cobb angle has to be fully automated, so users can employ this equipment without any personal mistakes. As a result, it can be used by assistants, without the involvement of orthopedists. This fact can lead to cheapening of the screening of this disease, since the instrument can be used in schools for checking a great number of children at the same time.

8. Conclusion

According to our results:

1. An electronic moiré equipment-based measurement and processing system is capable to identify the level of the Scheuermann's disease by calculating the Cobb angles from the shape of the spine line.
2. Regression and correlation analysis involve the identification of the relationship between X-ray-based results and our recommended method.
3. It was proved that the recommended extreme search method may be an alternative to the classical method.

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