




Supporting of Postural Deformities Diagnosis Using 3D Scanning

Robert Sitnik¹ , Jakub Michoński¹ , and Wojciech Glinkowski² 

¹ Warsaw University of Technology, Warsaw, Poland
r.sitnik@mchtr.pw.edu.pl

² Medical University of Warsaw, Warsaw, Poland

Abstract. Traditionally posture deformity assessment for screening purposes is performed by visual examination of patient's body by an expert. During further follow-up of the diagnosed deformity full spine, X-Ray 2D images are acquired. 3D medical imaging (Computer Tomography and MRI) is used when the spinal surgery is considered. Visual examination is subjective and is strongly dependent on expert knowledge. X-Ray and tomographic imaging exposure can be contraindicated in some cases (i.e. pregnancy). During last two decades, the dynamic development of methods and systems for 3D scanning and algorithms for measurement data analysis is observed. 3D scanning is successfully applied in modern industrial production lines, documentation of cultural heritage and human body analysis. Recently, algorithms for data analysis allow for 100% inspection of complex geometry and have increasing support for control of the technological process parameters on the base of calculated deviation between measurement and assumed 3D model. In this paper, we present an alternative approach for back posture analysis based on structured light 3D scanning. We present three different systems: mobile solution for prescreening of back shape, full body 3D scanner for monitoring of posture deformities and 4D scanner for dynamic analysis. Such a three-stage system fit into the idea of evidence-based medicine. Each of presented devices produces 3D geometry data representing the surface of patient's body. Each of them has also accompanying software that has been developed for processing of geometry data into a final form that is easily interpreted by medical experts (angles, asymmetries, 3D models, changes in time of analyzed measures, etc.).

Keywords: 3D scanning · Posture analysis · Faulty posture · Scoliosis · Surface topography diagnostics

1 Introduction

The pervasive occurrence of posture deformities, like scoliosis, often becomes observed among children, adolescents and elderly, with both cosmetic and functional consequences. Measurements are needed to objectively analyze the condition, and they allow for monitoring the progress of changes. The deformities of the spine may appear in an older population with vertebral compression fractures due to osteoporosis. The forward

bending test, widely used in scoliosis screening, is associated with high false-positive rates. Existing and used instrumentation are indicated for the qualitative and/or quantitative assessment of the human posture. Direct surface measurement of the human posture by digitization could increase the predictive value of detecting scoliosis without sacrificing sensitivity [1, 2].

Currently, existing gold standard for faulty posture analysis is the usage of radiography, which delivers a certain dose of radiation [3]. Radiation exposure is an issue for patients who require frequent radiographic examination for diagnosis, scoliosis monitoring, and treatment [4, 5]. It is especially important for adolescent and pregnancy. Nash et al. estimated that the increase in risk due to X-ray radiation ranges from 3.4 to 15 per million [6] if teenage patients with scoliosis are subjected to an average of twenty-two radiographs over three years. Technological improvements reduce the radiation dose [7] significantly, but the risk still exists.

A promising alternative or at least supporting tool could be the usage of contactless optical three-dimensional (3D) systems which are based on safe white light illumination. Such systems are becoming more frequently recommended for back shape analysis and to estimate the curvature of spinous processes and the trajectory of the spine line. First attempts of using a visible spectrum camera have been made using photogrammetric techniques [8]. However, due to active nature of measurement process Moiré [9] and structured-light-projection-based systems [10, 11] are the most appropriate for three-dimensional evaluation of the spine. Another optical 3D scanning technique that has been implemented for postural deformities analysis is laser triangulation [12].

One of the important aspects is a numerical analysis of the measured surface followed by identification of anatomical structures that are visible on the body surface. Automatic localization of anatomical landmarks on the back surface was first proposed by Drerup and Hierholzer in 1987 [13]. They use as source data geometry calculated from rasterstereographic surface measurements. They calculate curvature-based features to detect the localization of landmarks, and later they calculate the three-dimensional spinous processes line in patients with mild to moderate scoliosis. Calculation of the spinous processes line may be useful for physicians, therapists, patients, and their parents to better visualize the deformity.

Surface topography measurements may be useful for screening, diagnosis, and monitoring of faulty posture cases. Optical systems have been found to only be more useful than radiographic, and rasterstereographic data for cases of scoliosis with Cobb angles below 50° [14]. However, this comparison has been made for measurement from one direction only. A new generation of 3D imaging devices, full body scanners, produces significantly more information than conventional surface topography [15, 16].

In this paper, we present three measurement systems with accompanying software that supports screening and diagnosis of the back surface. First, of them is based on one-directional back surface imaging with screening capability. Second is developed as four directional, full body stationary set-up with fully automated calibration and measurement functions. The last system is still in development phase, and it is devoted to movement analysis.

2 Structured Light Method

The structured light method, also categorized as active triangulation, includes both projected coded light and sinusoidal fringe techniques [17, 18]. Depth information of the object is encoded into a deformed fringe pattern which is recorded by an image acquisition sensor. Although related to projection moiré techniques, the shape is directly decoded from the deformed fringes recorded from the surface of a diffuse object instead of using a reference grating to create moiré fringes. Two other related techniques use projected random patterns and a trilinear tensor. This method is involved in measurement systems working in CAD/CAM industry, especially in automobile and aviation one. In addition, the medicine and computer graphics also employ this technique. In this technique, the measurement accuracy may be achieved by one part in 10,000, which means that for 1 m working volume 0,1 mm uncertainty is achievable.

Main advantages of the structured light method are easy implementation, no moving parts if a computer controlled DLP is used, fast image acquisition and processing. The main weakness of this method is connected with the high cost of a DLP projector, however recently quick decrease of prices can be observed.

The method implemented in the first two systems presented in this paper is based on a projection of shifted sine patterns and Gray codes [19] on the surface under investigation. Exemplary images are presented in Fig. 1. As a result of measurement set of 3D coordinates (x, y, z) is calculated. It is called a cloud of points. An exemplary calculated cloud of points is presented in Fig. 2.



Fig. 1. Exemplary images from measurement sequence: sinusoidal pattern (left) and Gray code (right)

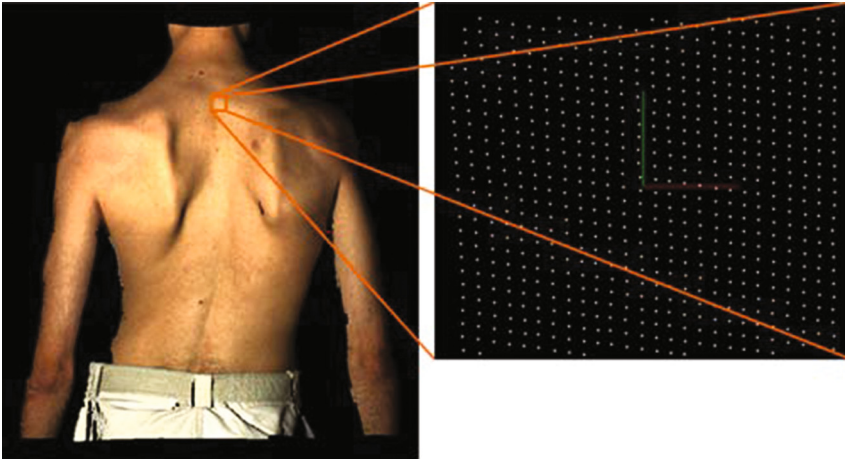


Fig. 2. An exemplary cloud of points from the back surface measurement

3 Imaging Systems

3.1 Mobile, Single-Directional Screening Set-up

This system is composed of a detector and a projector rigidly connected together and boxed. It is mounted on a tripod to adjust working volume for each patient independently (see Fig. 3). System parameters are 1,2 m × 1,2 m × 1 m – working volume, 4 s – acquisition time, approximately 1 million of measurement points. Real efficiency in screening application is between 100 and 200 measurements per day. It mostly depends on the organization of measurements.

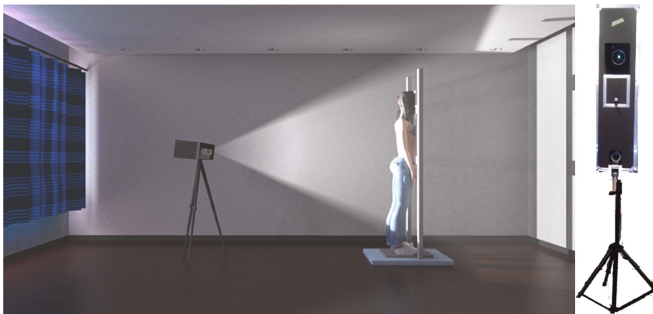


Fig. 3. Single directional set-up: visualization (left) and a photo of the system (right)

3.2 Four-Directional, Full Body Stationary Set-up

The system consists of four directional measurement heads that simultaneously capture the visible 3D shape of the human body (Fig. 4). During simultaneous measurement

from four heads, separation of their spectrum is used. Each of the directional heads captures the 3D shape of visible part of the human surface by using a different range of the spectrum. By combining four directional clouds of points, a full 3D human surface representation is created. System parameters are $1,5\text{ m} \times 1,5\text{ m} \times 2\text{ m}$ – working volume, 2 s – acquisition time, approximately 4 million of measurement points. This system is mostly used for supporting the diagnosis, monitoring, and brace design. It is located at The Baby Jesus Clinical Hospital in Warsaw.

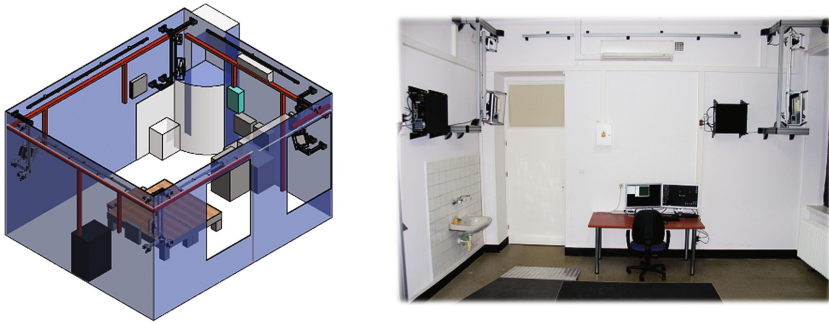


Fig. 4. Full body 3D scanner: schematic view (left) and a photo of real implementation (right)

3.3 4DBODY Set-up

This system is currently developed. It uses modified, single-frame structured light method [11]. It consists of four directional modules separated spectrally. It allows to achieve up to 120 Hz acquisition speed due to hardware synchronization between all

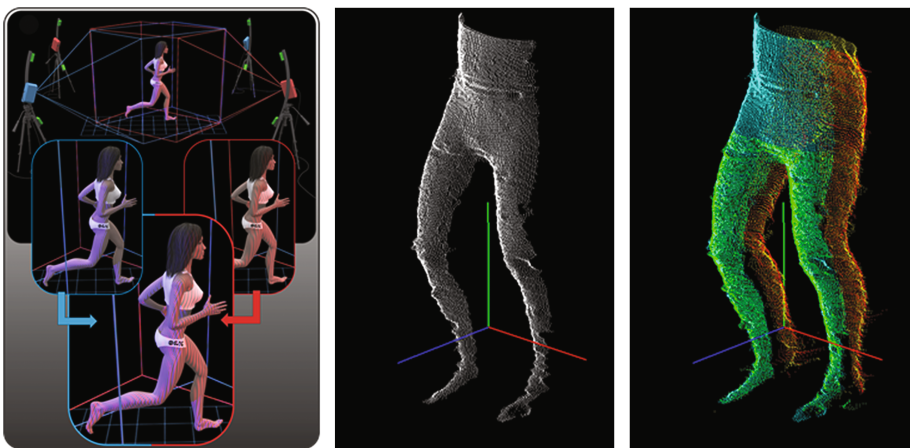


Fig. 5. Concept of 4DBODY system: visualization of full body measurement (left), single directional measurement (middle) and whole body scan (right)

system components. Its visualization is presented in Fig. 5. Application of simplified version of this system is discussed in [20].

4 Supporting Screening and Diagnosis of Back Surface

4.1 Preprocessing of Measurement Data

3D data from measurement are sometimes noisy (due to thermal noise on CCD/CMOS detector) and there are existing some incorrectly calculated points (outliers). In most cases, Hausdorff filtering is used followed by low pass filtering (see Fig. 6). For one-directional system also border elimination is applied due to higher errors on edges of measurement data.

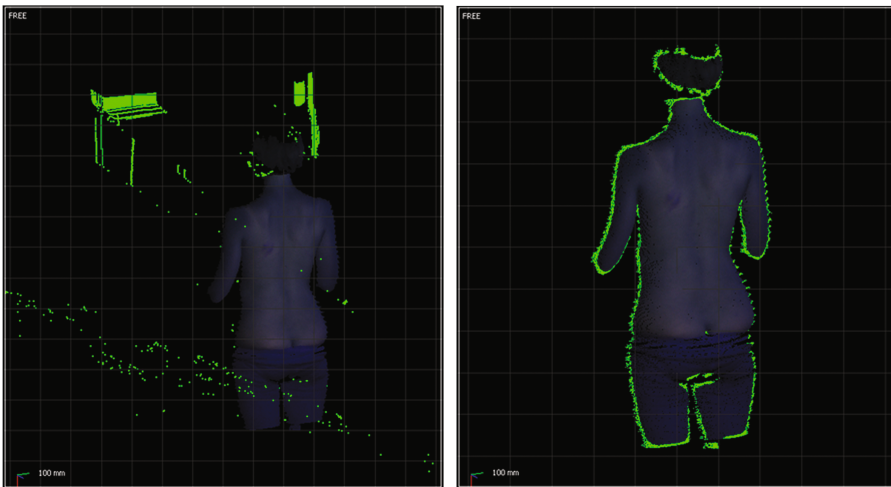


Fig. 6. 3D data preprocessing: Hausdorff filtering (left) and border removal (right)

4.2 Anatomical Landmarks Detection

There are several anatomical structures used to calculate indices for spine deformity assessment. These structures represent skeletal topographic points characteristically visible on the surface (e.g. lower angle of scapula) or unique areas of the body (e.g. axilla). Locations of other landmarks are arbitrarily defined (e.g. point on the shoulder above the axilla). The common feature of those structures is that their position is influenced by the shape of the spine which may facilitate deformity diagnosis using only topographic data. The indices addressed in our study are POTSI [21] and DAPI [22], which impose the selection of anatomical structures to discover (see Fig. 7). Also, estimation of spinal curvatures in the sagittal plane is performed, as well as vertical balance angles, calculated using the precalibrated plumb line. By merging the lists of landmarks required for calculation, the following anatomical structures were selected:

- the vertebral prominence of C7,
- top of the intergluteal furrow,
- left and right shoulder (points on the shoulder immediately above the axillae),
- left and right axilla,
- most proximal points on both sides of waist,
- posterior superior iliac spines (left and right),
- inferior angles of the scapula (left and right).

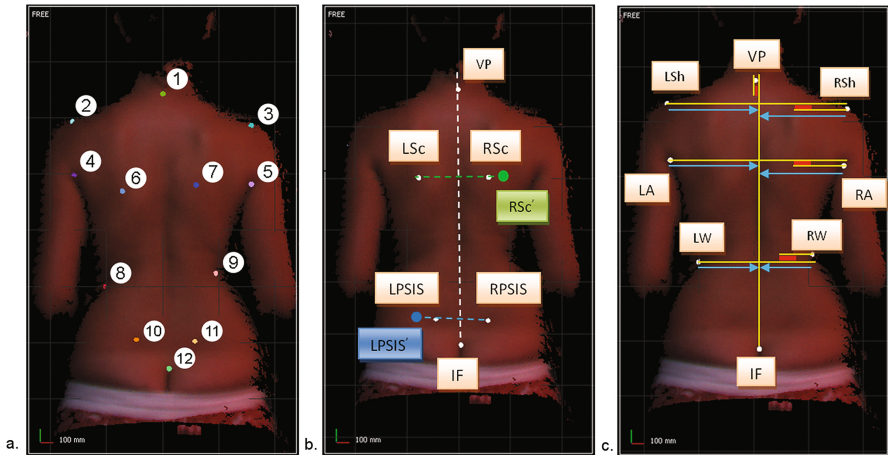


Fig. 7. Anatomical landmarks used in this study (left): 1 – vertebra prominens, 2, 3 – shoulders, 4, 5 – axillae, 6, 7 – scapulae, 8, 9 – waist line, 10, 11 – posterior superior iliac spines, 12 – natal cleft; DAPI (middle) and POTSI (right).

These anatomical landmarks are detected by using a mixed geometrical and expert knowledge model [23]. The average model from learning set is mixed with local curvature based model from which individual landmarks are detected.

The average model is based on a learning set of data containing landmarks indicated manually by experts on the surface of point clouds representing patient's back obtained from the measurement. For each measurement, the specialists (of 4 physiotherapists and 4 orthopedic surgeons) were requested to select all possible landmarks (based on a list supplied by the application used for this purpose, containing all the structures mentioned above) without the knowledge about the position of landmarks selected by the rest of the staff. Altogether, a total of 23 measurements were examined. The average age of patients was 24.7 (minimum 23, maximum 26), with a sex ratio of 11 females and 12 males. The data were supplemented by information about the region of interest for every measurement, detected automatically using the developed algorithms. It should be mentioned that the mean model was generated only on the basis of healthy (assessed by the experts) subjects, to present a good reference frame for the recognition process. Finally, Voronoi diagrams are generated (see Fig. 8).

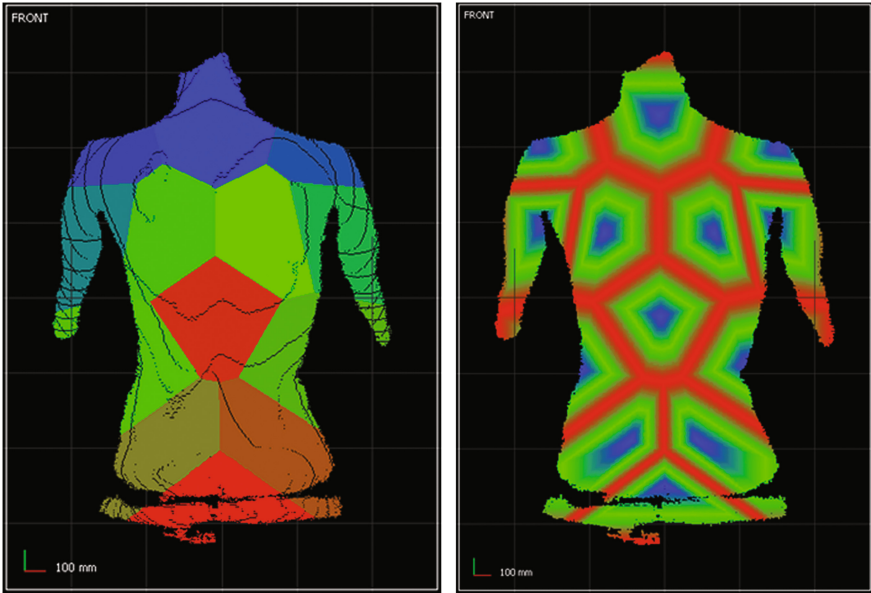


Fig. 8. Average model represented by Voronoi diagram (left) with distance weights (right)

After validation on a representative set weight factor has been established to 50%. Exemplary detection of anatomical landmarks is presented in Fig. 9.

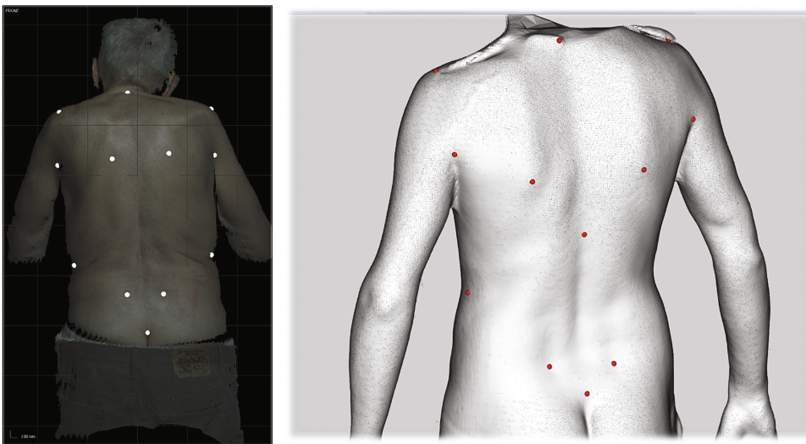


Fig. 9. Exemplary results of anatomical landmarks detection

4.3 Posture Analysis and Reporting

After detection of anatomical landmarks, many different indexes can be calculated. Depending on the case and the goal of the study one could choose one of the existing

parameters or even define their own. In Fig. 10 an exemplary report from the screening application is presented where most of the existing posture analysis metrics are calculated.

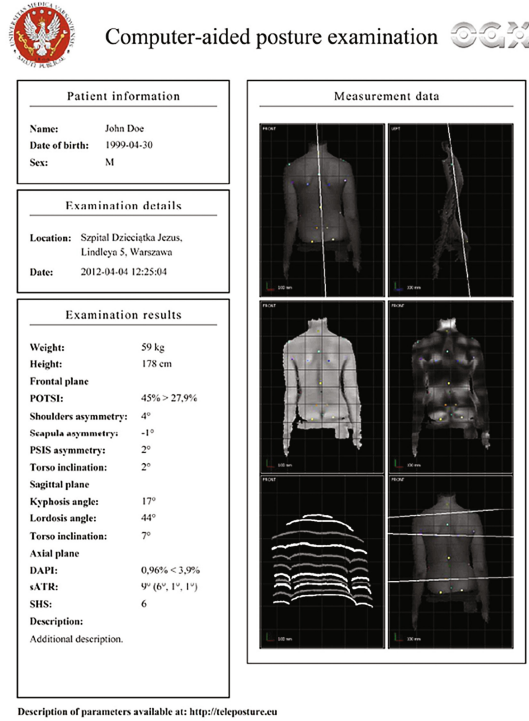


Fig. 10. Exemplary report from screening application software

4.4 4D Data Analysis

4D data require a different approach to data analysis [20]. In this application data are transferred to a musculoskeletal model. To achieve this goal 4D data have to be simplified to skeleton form with virtual markers. In Fig. 11 main algorithm steps allowing for such transformation are presented. The main steps of the algorithm are (they are performed for each frame separately):

- segmentation of lower body segments based on analysis of slices geometry,
- calculation of each bone segment,
- calculation of markers location in relation to bony segments.



Fig. 11. The algorithm of virtual markers calculation: initial data (left), segmentation by slicing (middle) and final bones and markers (right)

The additional step of calculation is temporal analysis when outliers (produced by noisy and erroneous frames) are filtered out. Presented algorithm has been validated [20] by existing gold standard – VICON system. Results of validation prove that this methodology could be used as an alternative for movement analysis.

5 Conclusions

Implementation of 3D scanning technology supported by ICT tools proves to be a promising alternative to traditional X-Ray approach for faulty posture assessment and analysis. Usage of structured light systems is radiation free and thus could be repeated as frequently as required. Measured data with analysis result could be also stored in computer databases and used for monitoring of posture parameters.

Presented systems have been used for massive posture screening programs in Poland. More than 25 000 of measurements has been performed [24].

Our future works will be focused on validation of applicability of these techniques in supporting of rehabilitation processes.

Acknowledgements. Works described in this article are part of the projects NR13-0020-04/2008, NR13-0109-10/2011, PBS3/B9/43/2015, which has been funded by the National Centre for Research and Development with public money for science and TLEMsafe project, which is funded by European Commission's 7th Framework Programme.

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