Modeling of human spinal column and simulation of spinal deformities

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1. Introduction

Modeling and simulation is widely used in all domains as resourceful tools in design, enhancement, improving or forecasting behavior of different systems. A wide range of software is available to aid solving engineering problems. However, there are systems, such as the biological ones, to which modeling and simulation is a very difficult task. The difficulty originates in two essential features:

- human body parts are very irregularly shaped;
- anthropometrical normal data is very scattered, regarding age, sex, race, profession, local environment traits and so on.

Therefore, biological models are not yet developed on large scale even though they would be very useful in investigating and monitoring patients suffering of widespread diseases. However, there is an encouraging start in modeling different parts of human body, such as feet [1], arms [2], mobile bones of the head [3] etc. The purpose of modeling is either depicting abnormal anatomical shapes or designing of devices such as prosthesis.

The present work focuses on the class of spinal deformities, which are very common in now-days. Most individuals suffer of mild or severe spinal column deformities, such as scoliosis, lordosis, kyphosis or combinations of these. Deformities cause diminution of personal comfort and of physical or intellectual capacity of effort. When severe, deformities bring on large distortions of thorax shape and alteration of respiratory process. Such spinal diseases occur frequently at school-age population, due to incorrect posture and/or to improper desk design and less frequently to adult population, due to sedentary activities (teachers, librarians, IT specialists etc.). The elder population also suffers because of irreversible bone alteration. Plenty of statistics describe the prelevance of such diseases in different places of the world, taking into account a lot of aspects such as: age, sex, profession, life standard etc. [4-6].The studies emphasize very detailed the importance of identifying early stages of spinal deformities because of cautious prognostic and very high costs of treatment [7].

Engineering sciences offer a large series of equipments to investigate the human bone system. Among the methods of investigation in use, the most common are X-ray, CT or MR imaging, Moire topography, digital ultrasonic mapping and optical scanning [8-17]. The stating order of these methods is chronological regarding the implementation and inversely from invasive character standpoint.

Countries which develop long term healthcare programs always include spinal deformities among the main issues to investigate and monitor, especially to school children and persons involved in specific professional activities. The main problems in tracing and monitoring spinal deformities consist of:

- finding a quick and less invasive method of investigation;
- establishing a set of numerical parameters to describe completely the column's shape;
- storing of a large amount of data considering the big number of subjects in the database;
- accessing data and evaluating the evolution of patients.

In order to model the spinal column and simulate its behavior, considering a long-term monitoring of an extended sample of population, the following workflow was conceived (Fig. 1).
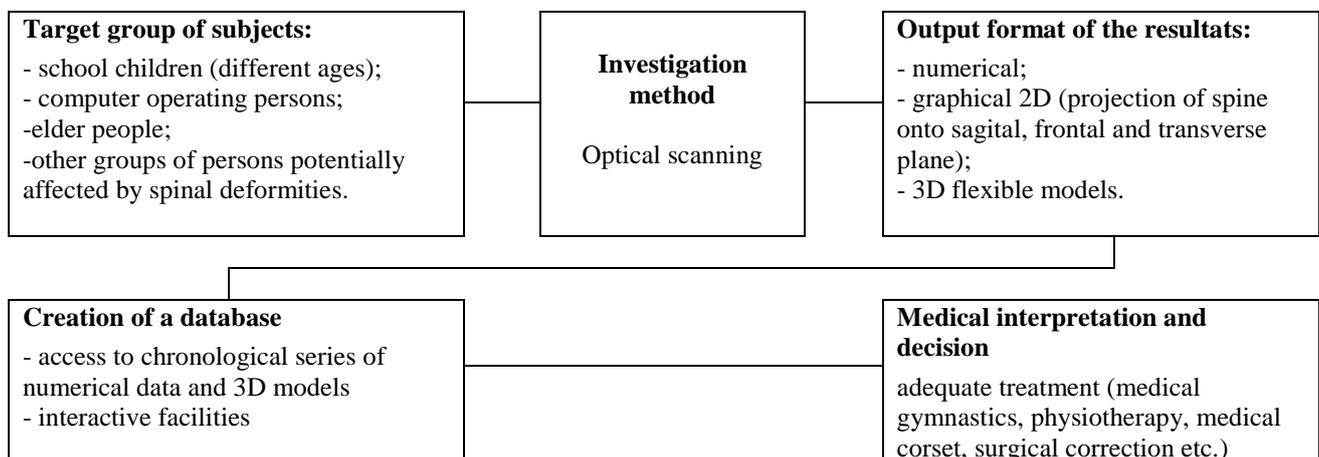

Fig. 1 Workflow of the biometric investigation and monitoring

The text-boxes in figure 1 indicate the logical steps to follow from establishing the target group of subjects to physician's decision regarding the results of a complete, objective and non-invasive investigation. The lower text contains the concrete goals to fulfill at each step.

2. Equipment and software to provide data for modeling

As Fig. 1 shows the choice for the investigation method went to a totally non-invasive method, based on optical scanning.

A team of multidisciplinary specialists developed a diagnosis method based on the equipment offered by the Canadian Company InSpeck, specialized in 3D optical measurement digitizing using non – laser technology. The technical team chose to implement the system InSpeck 3D Halfbody, which needs three cameras (Fig. 2, a). The 3D cameras are Mega Capturor II digital cameras type (Fig. 2, b). The optical image acquired by each camera is turned into a signal, sent to a PC, where the software FAPS 5.5 (Fringe Acquisition and Processing Software) creates a 3D virtual model. The second software in the package – EM 5.5 (Editing and Merging) – allows complex processing of data. 3D digitization technique is meant to render a three-dimensional copy of the physical surface placed in front of the cameras.
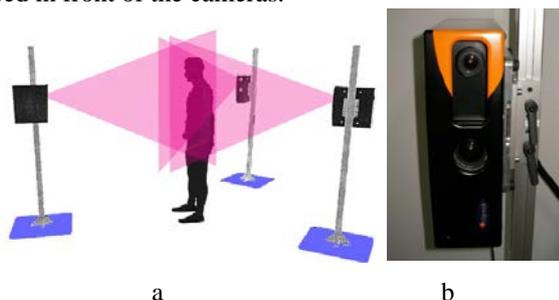

a   b

Fig. 2 a) Imaging in Halfbody configuration b) InSpeck 3D Mega Capturor II digital camera

The equipment InSpeck is an all-purpose imaging system, so that a special software, specific for the spinal column, was required in order to acquire data. A set of special markers was designed and manufactured to match the reference point of the vertebra – the spinous process. Figure 3 shows the position of 29 markers, attached to 23 vertebrae (C1…C7, T1…T12, L1…L5, S1…S3), shoulders (U1 and U2), scapulas (O1 and O2) and iliac crests (P1 and P2).

Determination of postural parameters, spinal characteristic distances and angles and, finally, global deformities need the knowledge of vertebrae coordinates along a zone as extended as possible. The practical measurements included a long segment of the spine comprising the vertebrae from C7 to S3. In Fig. 4, a is rendered an image of the vertebral spine. Different colors and symbols are assigned to cervical (C1…C7), thoracic (T1…T12), lumbar (L1…L5) and sacral (S1…S3) segments.

For a better description of posture and deformities, six supplemental markers picked coordinates of shoulders (U1 and U2), scapulas (O1 and O2) and iliac crests (P1 and P2).

As the equipment is able to pick 3D coordinates, the characteristic parameters of spine are defined within
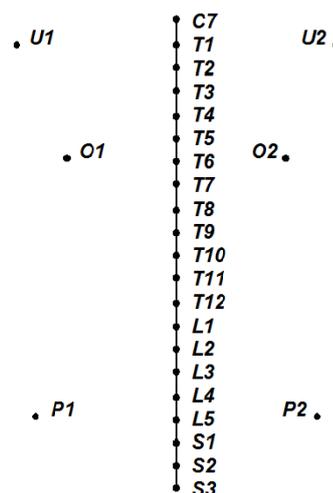

Fig. 3 Position of 29 markers to indicate the points where 3D coordinates are picked

one of the three anatomic planes (Fig. 4, b): xy –frontal plane, zy –sagital plane and xz –transversal plane.
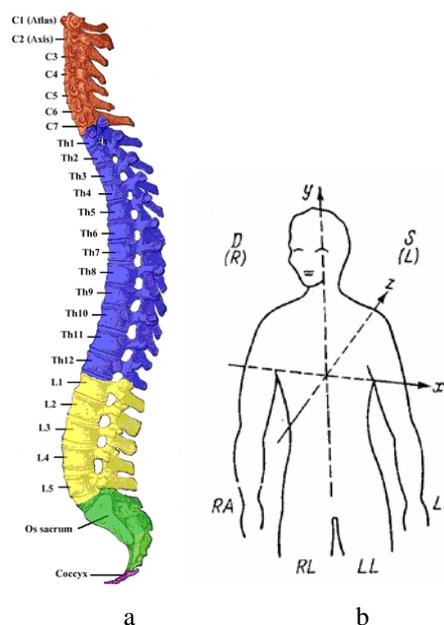

a   b

Fig. 4 a) View of vertebral column in sagital plane and symbols of vertebrae for the cervical, thoracic, lumbar and sacral zone; b) Position of anatomic planes defined to an orthogonal reference system xyz

Knowing 29 triplets of coordinates (x,y,z), a large series of parameters can be defined. In tables 1, 2 and 3 are presented the significant parameters of the vertebral column, as proposed by the authors.

Beside the parameters of the vertebral column within the projection planes, the effective lengths in 3D measurement should be also considered: total length (from C7 to S3), thoracic length (from C7 to L1) and lumbar length (from L1 to L5).

The hardware configuration and the software facilities of FAPS 5.5 and EM 5.5, previously mentioned, were used to create an ASCII file, in *.txt format, containing numerical data of the 29 measuring points. The file is meant to be exported to an advanced processing program.

Table 1

Parameters in sagital plane (zy)

Parameter	Definition	Scheme
Total trunk inclination	angle between the vertebrae line (C7 – L5) and the vertical axis containing C7	*C7, L5, y, α*
Thoracic kyphosis	angle between the vertebrae line (C7 – T1) and vertebrae line (T12 – L1)	*C7, T1, T12, L1, α*
Lumbar lordosis	angle between the vertebrae line (L1 –L2) and vertebrae line (L5 – S1)	*L1, L2, L5, S1, α*
Sacral angle	angle between the vertebrae line (S1 – S3) and the vertical line containing C7	*C7, S1, S3, y, α*

Table 2

Parameters in frontal plane (xy)

Parameter	Definition	Scheme
Pelvic obliquity	angle between pelvic line (P1 – P2) and a horizontal line	*P1, P2, α*
Shoulder obliquity	angle between shoulders line (U1 – U2) and a horizontal line	*U1, U2, α*
Scapula distance right	distance between the top of the right scapula and the scapulas line projected along y – axis	*d dr, C7, O2, O1, y, d st*
Scapula distance left	distance between the top of the left scapula and the scapulas line projected along y – axis	
Right scoliotic deformation	angle between vertebrae line (C7 – T1) and vertebrae line (T11 – T12)	*C7, T1, T11, T12, α*
Left scoliotic deformation	angle between vertebrae line (T11 – T12) and vertebrae line (S1 – S3)	*T11, T12, S1, S3, α*
Lateral inclination	angle between vertebrae line (C7 – S1) and the vertical line containing C7	*C7, S1, y, α*
Cobb angle	angle between the perpendiculars to vertebrae line (C7 – T1), respectively line (L4 – L5)	*C7, T1, T11, T12, L4, L5, α*

Table 3

Parameters in transversal plane (xz)

Parameter	Definition	Scheme
Pelvic rotation	angle between the pelvic line (P1 – P2) and scapulas line (O1 – O2)	*P1, P2, O1, O2, α*

The newly developed program, written as Visual Basic Application, was designed aiming the following requirements:

• development of a data basis containing a minimum set of information about the patients. The information should be accessed selectively, using different filters and should allow introducing and saving new data;

• import of data (coordinates of vertebrae) from an *.xls file;

• automated processing of data in order to obtain 16 parameters of posture or deformity;

• numerical and graphical display of results;

• print of an investigation report containing complete information about the patient (personal characteristics – such as name, age, profession – numerical and graphical results of investigation and notices of the physician if necessary).

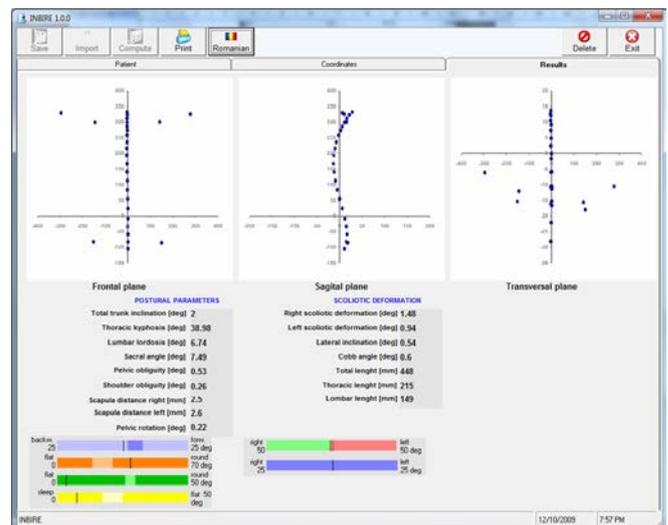The graphical interface of the program, named INBIRE is presented in Fig. 5.

Fig. 5 Image of results' display

3. Modeling of vertebrae and simulation of column deformations

Numerical parameters vary in large ranges and plane projections are not intuitive enough for the physician to establish a quick and correct diagnosis. It takes a great deal of time to correlate over 20 numerical characteristics even though graphical representations are partly helpful. The aim of a large scale investigation is both efficiency and precision. Thus, a 3D flexible model is welcomed.

Modeling of the spinal column is a difficult task so that the literature mentions only a few attempts to fulfill it [18-20]. Taking into account the specific problems occurring in modeling biological parts, it was conceived the workflow presented in Fig. 6.

The program chosen to work in was 3Dmax. The general initial data consider the following elements:

- The spinal column is a complex biological structure, containing 33 - 34 vertebrae, 344 joints and 24 intervertebral discs.
- There are 5 distinct segments of the column: cervical (7 vertebrae), thoracic (12 vertebrae), lumbar (5 vertebrae), sacral (5 vertebrae stiffed together) and coccyx (4-5 rudimentary vertebrae).
- The column axis is 3D shaped curve:

➢ curvature angle of approximately 9°, cervical zone (C1-C7);
➢ curvature angle of approximately 40°, thoracic zone (T1-T12);
➢ curvature angle of approximately 57°, lumbar zone (L1-L5).

- Statistical height of a vertebra is ~ 3 cm.
- For each zone the shape of the vertebrae is different.

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┌─────────────────┐      ┌─────────────────┐      ┌─────────────────┐
│ Model of specific│──────│ Segments of the │──────│ Spline          │
│ vertebra (cervical,│    │ column got from │      │ reprezenation of│
│ thoracic, lumbar,│      │ arrays of similar│     │ column's axis based│
│ sacral)         │      │ vertebrae (cervical,│  │ on physiological│
│                 │      │ thoracic, lumbar and│  │ 3D curvatures and│
│                 │      │ sacral zones)   │      │ angles          │
└─────────────────┘      └─────────────────┘      └─────────────────┘
         │                        │                        │
┌─────────────────┐      ┌─────────────────┐      ┌─────────────────┐
│ Standard model of│─────│ Personalized normal│────│ Personalized model│
│ the spinal column│     │ model (by scaling the│  │ with specific   │
│                 │      │ standard model) │      │ deformities     │
└─────────────────┘      └─────────────────┘      └─────────────────┘
                                  │
                         ┌─────────────────┐
                         │ Storage in a database│
                         │ and monitoring  │
                         │ evolution       │
                         └─────────────────┘
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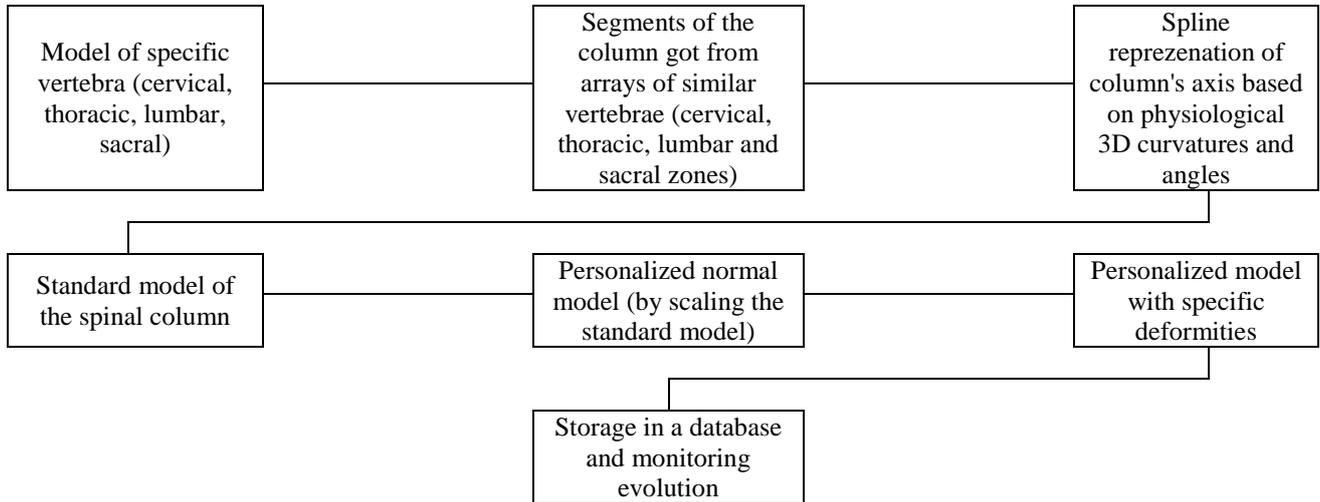
Fig. 6 General workflow of modeling the spinal column

Each type of vertebra was created starting from a regular shape, namely a cylinder. The functions of the program, such as Cut, Chamfer, Extrude, Smooth, Scale etc., allowed modifying the primary shape until it attained a perfect match with the vertebrae described in Grey's Anatomy Atlas [21].

Fig. 7 contains a print screen from the process of modeling a thoracic vertebra, whereas Fig. 8 renders all types of vertebrae together with their adjacent discs. To make the models more realistic, colors and textures were assigned to all elements. Specific zones of the column were obtained by cloning the appropriate type of vertebra and disc, in the required number. The function Array aligned the vertebrae along a spline, drawn using the physiological curvatures. The result is a standard model of spinal column (Fig. 9).

Personalized models result using the coordinates got from the program INBIRE, to trace the spinal axis. Functions PathDeform and Modifiers allow relatively easy and fast editing of the standard model. Fig. 10 illustrates through zoomed areas a column deformed by scoliosis.
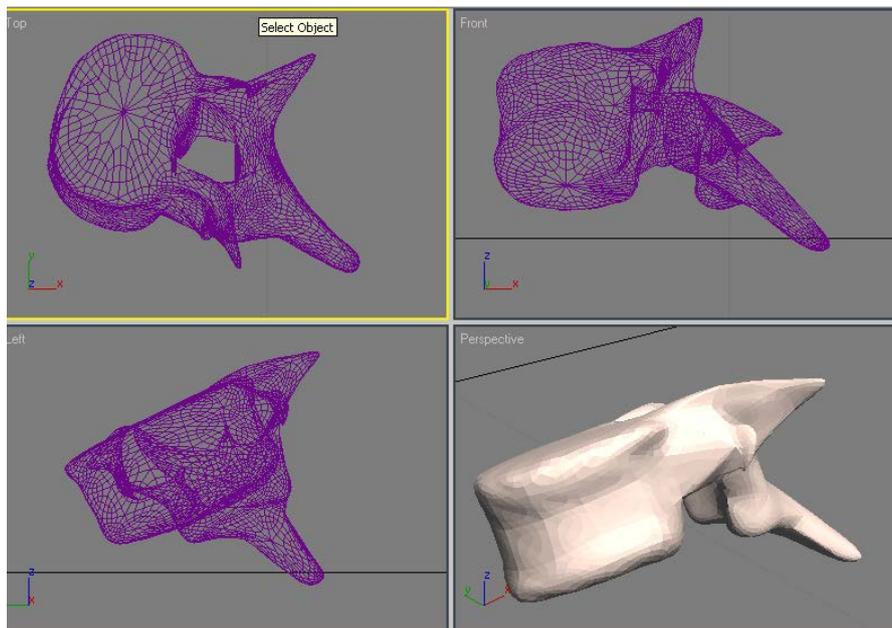

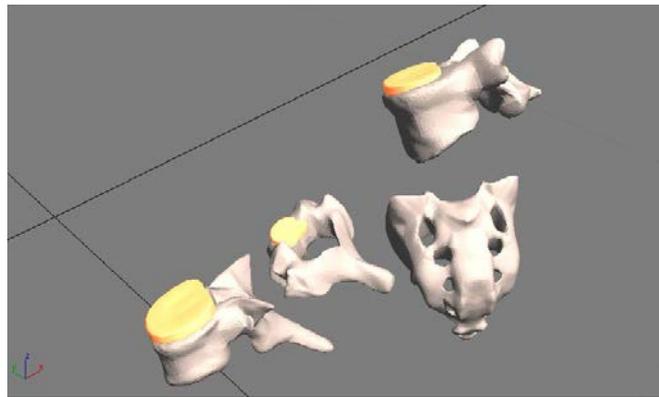Fig. 7 Modeling a thoracic vertebra in processing

Fig. 8 Models of single cervical, thoracic, lumbar and sacral vertebrae with adjacent discs
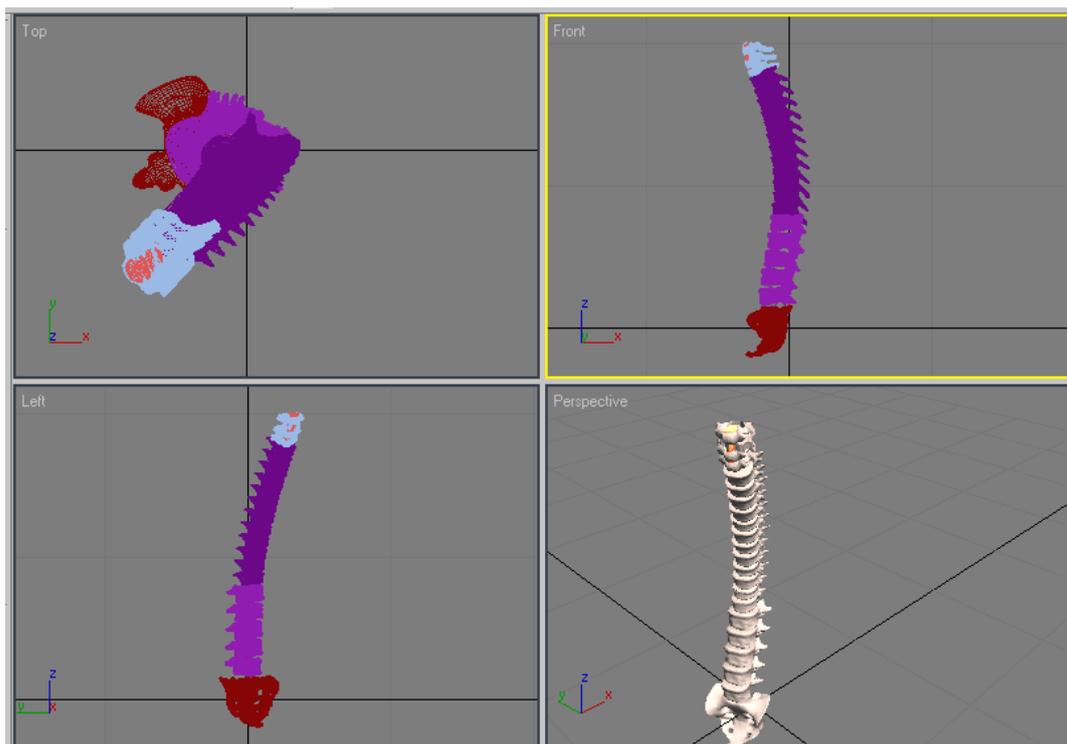

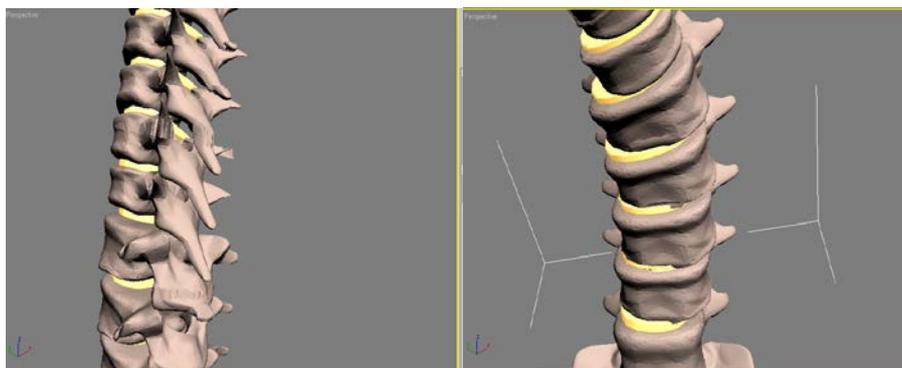Fig. 9 Standard model of the spinal column

Fig. 10 Details of a column deformed by scoliosis

4. Conclusions

Modeling and simulating is difficult for human body parts, especially for mobile ones. The present paper described the implementation of a totally non-invasive method of investigation for the spinal column, which is frequently affected by deformities. A large number of numerical parameters were suggested for the description of the column's shape. A special software – INBIRE – was developed to work with the all purpose imaging system InSpeck. The program provides an interactive database and the facility to export data to the modeling program 3Dmax. Using anthropometrical data, the individual vertebrae and finally the entire column was modeled as a standard. The coordinates provided by INBIRE allow modeling of personalized spinal columns, which can be stored and used by

physicians to monitor the evolution of the deformities.

The achievements of the research project contribute to development of local or national healthcare programs, bringing in numerical precision and efficiency in screening and monitoring spinal deformities, which are wide-spread, hard and costly to treat in advanced stages.

Acknowledgements

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MODELING OF HUMAN SPINAL COLUMN AND SIMULATION OF SPINAL DEFORMITIES

S u m m a r y

The paper presents the implementation of a totally non-invasive method of investigation for the spinal column, which is frequently affected by deformities. The equipment InSpeck (an all-purpose imaging system) is used as totally non-invasive investigation equipment. Specific software is developed to write information in an interactive database and to compute 16 numerical parameters, describing the column's shape, respectively the human posture. Data exported from the database allows modeling of personalized spinal columns, by means of modifying a standard model generated in 3Dmax. The entire procedure is meant to help major healthcare programs, which involve screening and monitoring large samples of population.