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Computer-Assisted Design and Finite Element Simulation of Braces for the Treatment of Adolescent Idiopathic Scoliosis using a Coronal Plane Radiograph and Surface Topography

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Abstract

Background: Orthopedic braces made by Computer-Aided Design and Manufacturing and numerical simulation were shown to improve spinal deformities correction in adolescent idiopathic scoliosis while using less material. Simulations with BraceSim (Rodin4D, Groupe Lagarrigue, Bordeaux, France) require a sagittal radiograph, not always available. The objective was to develop an innovative modeling method based on a single coronal radiograph and surface topography, and assess the effectiveness of braces designed with this approach.

Methods: With a patient coronal radiograph and a surface topography, the developed method allowed the 3D reconstruction of the spine, rib cage and pelvis using geometric models from a database and a free form deformation technique. The resulting 3D reconstruction converted into a finite element model was used to design and simulate the correction of a brace. The developed method was tested with data from ten scoliosis cases. The simulated correction was compared to analogous simulations performed with a 3D reconstruction built using two radiographs and surface topography (validated gold standard reference).

Findings: There was an average difference of 1.4°/1.7° for the thoracic/lumbar Cobb angle, and 2.6°/5.5° for the kyphosis/lordosis between the developed reconstruction method and the reference. The average difference of the simulated correction was 2.8°/2.4° for the thoracic/lumbar Cobb angles and 3.5°/5.4° the kyphosis/lordosis.

Interpretation: This study showed the feasibility to design and simulate brace corrections based on a new modelling method with a single coronal radiograph and surface topography. This innovative method could be used to improve brace designs, at a lesser radiation dose for the patient.

Keywords: Adolescent idiopathic scoliosis, brace simulation, finite element model

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1. **Introduction**

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional (3D) deformity of the spine, rib cage and pelvis. Bracing is the most common conservative treatment for moderate curve severity (Cobb angle between 20° - 40° assessed using a routine coronal radiograph). Thoraco-lumbo-sacral orthoses (TLSO) were originally fabricated using a plaster/cast technique, but now the fabrication process is being replaced by computer-aided design and manufacturing (CAD/CAM) methods (Wong, Cheng et al. 2005). CAD/CAM braces have proven to be as effective as the traditionally made ones, but require less fabrication time, material and are less expensive (Wong 2011).

In recent years, numerical design technologies based on 3D reconstruction, finite element modeling (FEM) and CAD/CAM have emerged in order to simulate the effectiveness of scoliosis braces (Clin, Aubin et al. 2010, Desbiens-Blais, Clin et al. 2012). Such technologies were used to assess and optimize the design process by enabling the testing and refinement of the brace efficiency before its fabrication and the delivery to the patients (Cobetto, Aubin et al. 2014). Braces made with CAD/CAM combined with finite element simulations have shown to be more effective and lighter than standard CAD/CAM braces (Cobetto, Aubin et al. 2016).

In order to build a FEM, a 3D model of the patient’s spine, rib cage and pelvis (internal skeletal anatomy) and a surface of the torso (external geometry) are necessary. To date, the 3D reconstruction of the internal skeletal anatomy requires a calibration object when taking sequential coronal and sagittal X-rays (Kadoury, Cheriet et al. 2007) or needs a factory-calibrated bi-planar radiographic system (Humbert, de Guise et al. 2009). The torso surface is generally acquired using a range sensing scanner based on structured light or laser ray (Pazos, Cheriet et al. 2007, Wong 2011).

The coronal radiograph is the standard for the diagnosis of scoliosis and follow up of the treatment in mild and moderate scoliosis. The sagittal radiograph is rarely acquired, which limits the use of FEM simulations to design braces. The sagittal radiograph is a supplementary dose of ionizing radiation, which also explains its limited utilization (Hoffman, Lonstein et al. 1989, Goldberg, Mayo et al. 1998). However, to date, CAD/CAM joined to finite element simulation of braces with the BraceSim platform
cannot be done without sagittal radiograph.

The aim of this study was to develop a 3D reconstruction and modeling method of the internal skeletal anatomy with a single coronal radiograph and a surface topography (Single X-ray method). We hypothesize that the accuracy and the effectiveness of braces issued from the CAD/CAM and FEM simulation based on this new 3D reconstruction technique are similar to those made with standard technique (Kadoury, Cheriet et al. 2007, Humbert, de Guise et al. 2009).

2. Methods
2.1. Patient Data
With the approval of our institutional review board, 10 cases were selected among the patients who received a brace treatment after getting a diagnostic of AIS or juvenile idiopathic scoliosis for this numerical study. Cases were selected in order to have a variety of curvature types (Table 1) and based on the availability of coronal and sagittal X-rays (for validation purposes) and a surface topography acquisition of the complete torso. X-rays were either from a low dose simultaneous bi-planar radiographic system (EOS, EOS imaging, Paris, France) or a single plane digital radiographic system (Fuji FCR7501S, Fuji Medical, Tokyo, Japan). A reference 3D reconstruction of their internal skeletal anatomy was built using two in-house validated software programs (NewSpine3D, described in Kadoury, Cheriet et al. 2007, IdefX, described in Humbert, de Guise et al. 2009). To do so, visible anatomical features were identified on both radiographs with various interactive tools and the 3D reconstruction was computed using mathematical algorithms. Both methods have a mean precision of at least 1.5 mm for vertebrae position and 5° for Cobb angle measurement. The 3D reconstructed models were used as reference for this study.

The external torso geometry was acquired using a surface topography scanner based on structured light (Inspect, Creaform, Quebec, Canada) or laser (O&P Scan, Rodin4D, Bordeaux, France). The 3D surface model was computed based on the external torso geometry in STL file format.
Table 1: Patients coronal and sagittal profiles; a- kyphosis was measured between T2 and T12 (normal values between 10° and 40°); b- lordosis was measured between T12 and L5 (normal values between 40° and 60°)

<table>
<thead>
<tr>
<th>SCOLIOTIC PROFILE IN THE CORONAL PLANE</th>
<th>PRESENTING DEFORMITY (COBB ANGLES)</th>
<th>SAGITTAL CURVES PROFILE</th>
<th>SAGITTAL CURVES</th>
<th>RADIOGRAPHIC SYSTEM</th>
<th>SCANNER TECHNOLOGY</th>
</tr>
</thead>
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<tr>
<td>P1  Single left lumbar curve 19°</td>
<td>Normal(^a) kyphosis Normal(^b) lordosis</td>
<td>34°</td>
<td>Low dose simultaneous bi-planar</td>
<td>Structured light</td>
<td></td>
</tr>
<tr>
<td>P2  Thoracic and lumbar curves 23°/26°</td>
<td>Hyper kyphosis Normal lordosis</td>
<td>45° 56°</td>
<td>Low dose simultaneous bi-planar</td>
<td>Structured light</td>
<td></td>
</tr>
<tr>
<td>P3  Thoracic and lumbar curves 39°/31°</td>
<td>Normal kyphosis Normal lordosis</td>
<td>34° 51°</td>
<td>Low dose simultaneous bi-planar</td>
<td>Structured light</td>
<td></td>
</tr>
<tr>
<td>P4  Single left lumbar curve 23°</td>
<td>Normal kyphosis Normal lordosis</td>
<td>37° 56°</td>
<td>Low dose simultaneous bi-planar</td>
<td>Structured light</td>
<td></td>
</tr>
<tr>
<td>P5  Single right thoracic curve 25°</td>
<td>Hyper kyphosis Hyper lordosis</td>
<td>56° 72°</td>
<td>Low dose simultaneous bi-planar</td>
<td>Structured light</td>
<td></td>
</tr>
<tr>
<td>P6  Thoracic and lumbar curves 23°/35°</td>
<td>Hyper kyphosis Normal lordosis</td>
<td>54° 48°</td>
<td>Low dose simultaneous bi-planar</td>
<td>Structured light</td>
<td></td>
</tr>
<tr>
<td>P7  Single Right lumbar curve 28°</td>
<td>Hyper kyphosis Hyper lordosis</td>
<td>56° 65°</td>
<td>Single plane digital Laser</td>
<td>Laser</td>
<td></td>
</tr>
<tr>
<td>P8  Thoracic and lumbar curves 39°/31°</td>
<td>Hyper kyphosis</td>
<td>45° 52°</td>
<td>Single plane digital Laser</td>
<td>Laser</td>
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</tbody>
</table>
2.2. Modeling of the spine, rib cage and pelvis with the Single X-ray method

The method used as input the coronal X-ray and the torso surface acquired using one of the topography systems presented in section 2.1. The two geometries were computationally superimposed in the custom developed graphical interface built using MATLAB 2016a (Mathworks Inc., Natick, USA). The X-ray was computationally scaled, so the spine and pelvis were adjusted to the size of the torso surface scan. Top corners of each vertebral endplate for vertebrae T1 to L5 were then digitized, as well as 4 landmarks along the iliac crests and the center of the left and right acetabula.

From a database of 10 3D deformable spine and pelvis models representing various types of scoliosis deformities, the model shape that best match the current case was chosen by the user. The choice was based on the spine curves visible on the patient coronal X-ray as well as on the coronal and sagittal projections of the surface scan. The 10 models were from of our in-house patient database (IRB was obtained from these patients for inclusion in the patient database and reuse of their clinical data). The models were previously built using the 3D reconstruction method of Humbert, de Guise et al. (2009) (Fig 1. A). The selected deformable 3D model was then morphed onto the digitized landmarks using a free form deformation technique (Delorme, Petit et al. 2003) in order to fit the coronal plane coordinates of each corresponding anatomical landmarks of the coronal X-ray. Anatomical landmarks coordinates in the sagittal plane from the presenting 3D model of the selected case were preserved (Fig 1. B)
A FEM of the spine and pelvis was created using Ansys 14.5 finite element package (Ansys Inc., Canonsburg, PA, USA). The FEM model of the spine and pelvis included the thoracic and lumbar vertebrae and intervertebral discs represented by beam and shell elements. The mechanical properties were taken from published and experimental data (Aubin, Dansereau et al. 1996, Perié, Aubin et al. 2004). Anterior or posterior displacements were applied to T1, as well as to a vertebra in the thoraco-lumbar/lumbar area, and a sagittal plane tilt of the pelvis was realized in order that the sagittal profile could best match the back’s shape as appreciated by the user from the superimposed surface scan. Using the FE model allows the user to prescribe movement for two vertebrae and the pelvis while the remaining vertebrae positions are interpolated by the model. The displacements of the spine and pelvis were computed by solving the FEM, and the resulting model shape was then displayed. The user was allowed to repeat this step up until a satisfying sagittal conformity between the deformable spine model and the actual patient torso shape was found (Fig 1. C).

The geometry of each rib was then defined by 1 point directly computed from the spine model and 4 points identified by the user on the coronal X-ray. The first point corresponded to the head of the rib, and was computationally approximated by the coordinates of the upper right or left endplate of the related thoracic vertebra from the deformable spine model. The four subsequent points were added on the coronal plane along the rib or along the sternum by the user. Their 3D coordinates were computationally derived from their projection on the anterior or posterior surface scan. The local thickness of the soft tissues, breast shape and shoulder blades was subtracted from the projections to obtain the final 3D coordinates. (Fig 2. A)

A FEM of the ribs, sternum, costal cartilages, soft internal and external tissue were added to the FEM model of the spine and pelvis using Ansys 14.5 (Ansys Inc., Canonsburg, PA, USA). The mechanical properties were taken from published and experimental data (Aubin, Dansereau et al. 1996, Perié, Aubin et al. 2004, Perié, Aubin et al. 2004, Clin, Aubin et al. 2011). The FEM model of the spine, pelvis rib cage and soft tissues was
validated and used as part of previous studies on CAD/CAM braces and simulation (Desbiens-Blais, Clin et al. 2012, Cobetto, Aubin et al. 2014).

2.3. Brace Design and Installation Simulation

In order to obtain a brace design model, displacements were applied using the FEM to the vertebrae to virtually align the spine in the sagittal plane. The resulting virtual corrected torso surface was used as an input to design the brace shape (Cobetto, Aubin et al. 2014). The geometry was imported to a CAD/CAM orthosis design software (Rodin4D, Groupe Lagarrigue, Bordeaux, France). Tools and features of the software were used to deepen corrective regions, to create brace’s outlines and to add straps fixation.

A FEM of the brace was then modeled with quadrilateral shell 4-node elements and polyethylene material properties (Clin, Aubin et al. 2007). The brace installation simulation was performed using a validated method (Desbiens-Blais, Clin et al. 2012, Cobetto, Aubin et al. 2014) in two steps: creation of the surface-to-surface contact between the brace model and the trunk FEM and application of forces on the straps. During the simulation, the pelvis was controlled in rotation and translation along the three axes and vertebra T1 was restrained in the transverse plane.

2.4. Assessment of the 3D reconstruction and the derived simulated brace correction

The spine 3D reconstruction obtained with the Single X-ray method was compared to a reference geometry built using a validated 3D method with two radiographs (Reference method). The single X-ray method and the patient reconstructions reference method were defined as independent variables. The following dependent variables were analyzed: analytical measurements of Cobb angles, thoracic kyphosis between T2-T12 and lumbar lordosis between T12-L5. These indices were computed for the reconstructed patient with no brace as well as for the simulated brace, and compared for the two reconstruction methods. A Shapiro-Wilk test for normality was realized to justify the use of parametric
statistical tests. T-tests for dependant samples (95% significance level) were performed using STATISTICA V10 computer software (StatSoft Inc., Tulsa, USA) to correlate results obtained from the in-house software for the 1-view reconstruction with results obtained using the 2-views reconstructions reference method.

3. Results

Computed angles for the developed Single X-ray method and the reference method are reported in Table 2, and simulated brace correction with both models is reported in Table 3. There was a mean difference of 1.4° and 1.7° for thoracic and thoraco-lumbar/lumbar Cobb angles respectively between the two methods. In the sagittal plane, the mean difference was 2.6° for the kyphosis and 5.5° for the lordosis. There was a mean difference of 2.8° for thoracic and 2.4° for thoraco-lumbar/lumbar Cobb angles when comparing simulated brace correction between the two methods. In the sagittal plane, the mean difference was of 3.5° for the kyphosis and 5.4° for the lordosis. Maximum differences in the coronal plane were of 4.2° and 3.1° for thoracic and thoraco-lumbar/lumbar Cobb angles before brace simulation and 7.6° and 4.2° for thoracic and thoraco-lumbar/lumbar Cobb angles with the simulated brace correction.

The detailed results for one case (P4) are presented in Fig. 2. For the Single X-ray method, the lumbar Cobb angle was reduced from 22° to 12° while for the model built with the reference method, the same angle was reduced from 20° to 12°.
Table 2: Computed analytical angles (in degrees) of the 3D reconstructed spine built with the reference and Single X-ray methods

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</thead>
<tbody>
<tr>
<td>P1</td>
<td>15.3</td>
<td>15.0</td>
<td>0.3</td>
<td>-18.8</td>
<td>-17.4</td>
<td>-1.4</td>
<td>34.3</td>
<td>38.8</td>
<td>-4.5</td>
<td>-46.3</td>
<td>-52.1</td>
<td>5.8</td>
</tr>
<tr>
<td>P2</td>
<td>22.9</td>
<td>27.2</td>
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<tr>
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<td>-2.1</td>
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<td>0.4</td>
<td>-22.5</td>
<td>-20.1</td>
<td>-2.4</td>
<td>36.5</td>
<td>34.4</td>
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<td>-0.8</td>
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<td>-3.1</td>
<td>-5.3</td>
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<td>8.4</td>
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<tr>
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<td>1.3</td>
<td>28.2</td>
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**ABSOLUTE MEAN**

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<td>0.7</td>
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Table 3: Computed analytical angles (in degrees) of the 3D reconstructed spine built with the reference and One X-ray methods and simulated brace correction

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<thead>
<tr>
<th></th>
<th>THORACIC COBB ANGLE</th>
<th>THORACO-LUMBAR/LUMBAR COBB ANGLE</th>
<th>THORACIC KYPHOSIS</th>
<th>LUMBAR LORDOSIS</th>
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ABSOLUTE MEAN

SD

P-VALUE
4. Discussion

This study showed the feasibility of reconstructing in 3D the anatomy of the spine, rib cage and pelvis. The developed innovative reconstruction method enabled to perform CAD/CAM and finite element simulation of braces for the correction of spinal deformities using a single coronal X-ray and the surface scan of the patient torso. The developed technique distinguishes itself from current techniques that necessitate at least a calibrated pair of radiographs (Delorme, Petit et al. 2003, Kadoury, Cheriet et al. 2007), with the advantage of lowering the cost and ionizing radiation exposure for patients.

The model was quite accurate in the coronal plane because the developed technique fully used the spine geometry features from the coronal radiograph. Also, it took advantage of the true dimensions of the surface scan to scale the size of the spine subjected to the magnification of the radiographic conical projection. The documented accuracy was below the 3° confidence range for manual or computer-assisted radiographic measurement of Cobb angles (Shea, Stevens et al. 1998, Aubin, Bellefleur et al. 2011).

As expected, accuracy was lower in the sagittal plane, as the estimated sagittal curvature of the spine relies on the available shape of the torso scan, as well as on the sagittal curvatures of the selected case from the database, which may differ from the actual case. The main limitation of our method is that the distance between the back skin and the spine depends on the thickness of patient’s soft tissues, which may vary according to patient’s morphotype. A certain level of experience is thus needed to estimate this thickness and therefore accuracy of sagittal curvatures adjustment is dependent on user experience.

Another limitation of the study was the limited number of cases in the database. However, one could assume that with the availability of a larger dataset, it would increase the capability to find a more similar case relative to the overall shape of the spine and axial orientation of the vertebrae, and therefore have a better fit in the sagittal plane. Yet the accuracy was found to be clinically acceptable, as it is similar to the measurement accuracy of sagittal plane radiographs. For instance, (Leroux, Zabjek et al. (2000))
documented a mean absolute difference of $5^\circ$ for the lordosis and $6^\circ$ for the kyphosis using a stereoradiographic technique and a linear correlation method to measure sagittal curvatures.

Two different technologies were used to obtain external torso geometries (structured light and laser). These two scanner technologies have an accuracy below 2 mm (Cheriet, Song et al. 2010, Knoops, Beaumont et al. 2017). Measurement differences between the two scan types are below the accuracy threshold required for a clinically meaningful brace simulation with the BraceSim platform. Therefore, using different body scan types does not affect the results of the current study.

3D reconstruction inaccuracies had no significant impact when used to design and simulate brace correction using FEM derived from the 3D reconstruction, as the difference in terms of the predicted correction also was within the clinical error of today's measurement methods when compared to results from 3D reconstructions used for bracing simulation. This new innovative method allows FEM simulations of braces on patients’ models obtained without a calibrated sagittal radiograph. As a result, more healthcare centers can benefit the use of FEM simulations for brace design in order to improve brace effectiveness.

5. Conclusions

This study showed the feasibility to build a 3D personalized patient model with a single coronal X-ray and a surface scan of the torso, which can be used to design and simulate braces. The documented accuracy of the reconstructed anatomy was $2^\circ$ in the coronal plane and $6^\circ$ in the sagittal plane, while the simulated braces derived from the 3D reconstruction had similar accuracy as compared to existing methods based on two radiographs. The developed Single X-ray method can be used as an alternate 3D reconstruction method for brace simulation when a sagittal X-ray is not available.

References


Figures

Fig 1. Steps to build the spine and pelvis models. A- Patient’s coronal X-ray and external surface scan and 3D deformable model of a spine and pelvis from a database; B– Scaling and mapping of the X-ray, surface scan and of the 3D deformable model; C– Sagittal adjustment of the spine and pelvis models.

Fig 2. Steps to build the rib cage model. A–Control points selected on each rib of the coronal X-ray and projection onto the sagittal plane using the surface and soft tissue thickness considerations; B–completed personalized patient trunk 3D geometry.
<table>
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<th>Reconstruction method</th>
<th>Computed 3D reconstruction of the spine curve and Simulated in brace correction</th>
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<td>Reconstruction with reference method</td>
<td><img src="image" alt="Computed 3D reconstruction of the spine curve (blue) and Simulated in brace correction (red) and computed Cobb angles" /></td>
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<tr>
<td>Reconstruction with Single X-ray method</td>
<td><img src="image" alt="Computed 3D reconstruction of the spine curve (blue) and Simulated in brace correction (red) and computed Cobb angles" /></td>
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Fig. 3 Computed 3D reconstruction of the spine curve (blue) and Simulated in brace correction (red) and computed Cobb angles
HIGHLIGHTS

- A 3D reconstruction method for brace simulation without sagittal X-ray was proposed
- A 3D patient-specific modeling method of spine, rib cage and pelvis was developed
- The method uses a coronal X-ray and a torso’s surface scan of the patient
- 3D reconstructions can be used to design and simulate orthopedic scoliosis braces
- Clinically acceptable accuracy was obtained