Simulation of orthotic treatment in adolescent idiopathic scoliosis using a subject-specific finite element model

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1. Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity of the spine, often progressing rapidly during the growth spurt. Severe scoliosis can lead to significant degradation of quality of life and functional impairment; the aim of early orthotic treatment is to slow down curvature progression until skeletal maturity. Efficacy of bracing has often been questioned (Negrini et al., 2010; Weinstein et al., 2013), and often relies on the orthotist's experience since objective methods to design and predict brace action are still in development (Cobetto et al., 2014).
A clinically-relevant method for the evaluation of brace simulation in AIS was recently presented (Vergari et al., 2015) and applied to preliminarily validate a finite element model (FEM) of the trunk.
The aim of this work was to improve the simulation of brace action on scoliotic trunks and to validate the model on a larger cohort.

2. Methods

2.1 Subjects

Forty-two subjects were included both retrospectively and prospectively in this study (38 girls and 4 boys between 7 and 17 years old, 26.2° ± 14.4° Cobb angle). All were diagnosed with AIS and prescribed an orthotic treatment. Stereoradiographs were acquired both at the moment of treatment decision and in-brace, between 0 (i.e. same day) and 7 months later. The study was approved by the ethical committee (CPP 6001 Ile de France V).

2.2 Finite element model

A previously described subject-specific FEM was automatically built (Vergari et al., 2015) from pelvic, spinal and ribcage 3D reconstructions (Aubert et al., In Press; Humbert et al., 2009).

2.3 Border conditions

The pelvis and T1 vertebra were displaced from the out of brace to the in-brace configuration, in order to maintain proper subject balance. Brace pad placement was retrieved from soft tissue deformation and radiopacity in radiographic images. Those pads acting on the ribcage were implemented in the simulation as cylindrical structures (485 nodes, 433 hexahedral elements, 0.01 MPa Young's modulus). Pads acting directly on the spine (e.g. in the lumbar region or on the back) were implemented by applying displacements to the corresponding vertebrae. Displacements were calculated from the 3D reconstruction of the subject with and without bracing.

2.4 Evaluation

Simulations were evaluated by calculating the root mean square error (RMSE) between the clinical indices as measured on the in-brace 3D reconstruction and those extracted from the simulation. Error tolerances (Table 1) were estimated by combining the measurement uncertainty involved in comparing two 3D reconstructions. Vertebral positions and orientations were also evaluated.

3. Results and discussion

Average computation time was about 15 minutes. Global RMSEs are reported in Table 1, while Figure 1 reports an example of brace action and simulation of spinal midline.
Errors were smaller than the defined tolerances in the lateral (kyphosis and lordosis), frontal (Cobb angle) and axial planes (axial rotation). All subjects presented an error in T1-T12 kyphosis smaller than the tolerance; 80 % of the subjects were in the tolerance range for the Cobb angle and apical axial rotation. 86 % of the subjects presented smaller errors than tolerance for torsion (5°) and 90 % for 3D rib hump (7 °).

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	T1/T12 Kyphosis	Cobb angle	Apical axial rotation
Tolerance	8 °	5 °	5 °
RMSE	2.5 °	4.1 °	3.9 °
Max error	6.7 °	8.7 °	9.3 °

Table 1. Global simulation errors and error tolerances

Global RMSE in vertebral position was 1.9 mm, with an error of 2.3 mm in lateral direction, 2.1 mm in antero-posterior and 0.9 mm in vertical direction.
In the previously presented work (Vergari et al., 2015), pad action on the ribcage was modelled by displacing those nodes corresponding to the pad region. Global errors were smaller in the present study, with a decrease of T1-T12 kyphosis RMSE of 1.2 °, for instance, 1.6 ° of Cobb angle and 3.1 ° in apical axial rotation.
Because of the measurement uncertainty of the 3D reconstruction used to build the out of brace and in-brace geometries, rib length is not exactly the same in the two cases. The previous method of pad implementation therefore induced local deformations and high local stresses due to lengthening, shortening or sharp bending of rib elements.

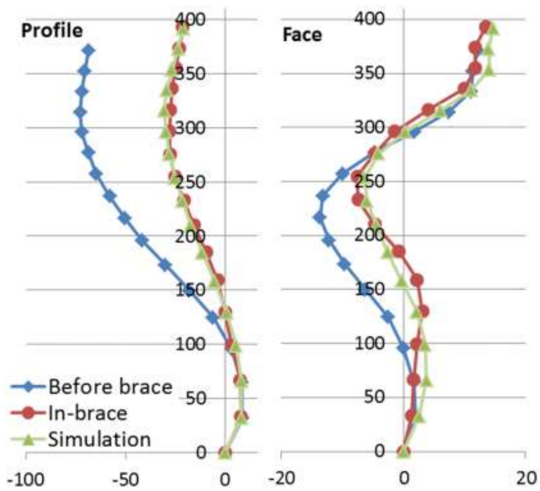

Figure 1 Spinal midline and vertebral locations (units are in mm)

Pads were explicitly represented and were implemented as solid objects acting by mechanical contact on the rib cage. This eliminates the local deformation that affected the previous version, yielding more natural in-brace geometry. The forces resulting on the pad can now be analysed to investigate brace comfort, and potentially be integrated in brace design.

4. Conclusions

This work provides a robust validation in 42 scoliotic patients of an existing finite element model for the simulation of brace action on the scoliotic spine. While validation should be pursued on a larger cohort, this model could potentially be applied in brace design and improvement.

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References

Aubert B, Vergari C, Ilharreborde B, Courvoisier A, Skalli W. In Press. 3D Reconstruction of rib cage geometry from biplanar radiographs using a statistical parametric model approach. Comput Methods Biomech Biomed Eng Imaging Vis.

Cobetto N, Aubin CE, Clin J, Le May S, Desbiens-Blais F, Labelle H, Parent S. 2014. Braces Optimized With Computer-Assisted Design and Simulations Are Lighter, More Comfortable, and More Efficient Than Plaster-Cast Braces for the Treatment of Adolescent Idiopathic Scoliosis. Spine Deformity. 2:276-284.

Humbert L, De Guise JA, Aubert B, Godbout B, Skalli W. 2009. 3D reconstruction of the spine from biplanar X-rays using parametric models based on transversal and longitudinal inferences. Med Eng Phys 31, 681-687.

Negrini S, Minozzi S, Bettany-Saltikov, Zaina F, Chockalingam N, Grivas TB, Kotwicki T, Maruyama T, Romano M, Vasiliadis ES. 2010. Braces for idiopathic scoliosis in adolescents. Cochrane Database Syst Rev. CD006850.

Vergari C, Ribes G, Aubert B, Adam C, Miladi L, Ilharreborde B, Abelin-Genevois K, Rouch P, Skalli W. 2015. Evaluation of a patient-specific finite element model to simulate conservative treatment in adolescent idiopathic scoliosis. Spine Deformity 3, 4–11.

Weinstein SL, Dolan LA, Wright JG, Dobbs MB. 2013. Effects of bracing in adolescents with idiopathic scoliosis. N Engl J Med. 369:1512:1521.