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Biomechanics

Evaluation of a Patient-Specific Finite-Element Model to Simulate Conservative Treatment in Adolescent Idiopathic Scoliosis

Claudio Vergari, PhD[a,*], Gwenael Ribes, MEng[a], Benjamin Aubert, MEng[a], Clayton Adam, PhD[a], Lotfi Miladi, MD[b], Brice Ilharreborde, MD[c], Kariman Abelin-Genevois, MD[d], Philippe Rouch, PhD[a], Wafa Skalli, PhD[a]

[a]*Arts et Metiers ParisTech, LBM, 151 bd de l'Hopital, 75013 Paris, France*
[b]*Department of Pediatric Orthopedics, Necker Enfants Malades Hospital, AP-HP, 149 rue de Sevres, 75743 Paris Cedex 15, France*
[c]*Pediatric Orthopaedics Department, Robert Debré Hospital, AP-HP, Paris Diderot University, 48 Bd Sérurier, 75019 Paris, France*
[d]*Department of Pediatric Orthopedics, Hospices Civils de Lyon, Claude Bernard Lyon 1 University, Lyon, France*

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Abstract

Study design: Retrospective validation study.
Objectives: To propose a method to evaluate, from a clinical standpoint, the ability of a finite-element model (FEM) of the trunk to simulate orthotic correction of spinal deformity and to apply it to validate a previously described FEM.
Summary of background data: Several FEMs of the scoliotic spine have been described in the literature. These models can prove useful in understanding the mechanisms of scoliosis progression and in optimizing its treatment, but their validation has often been lacking or incomplete.
Methods: Three-dimensional (3D) geometries of 10 patients before and during conservative treatment were reconstructed from biplanar radiographs. The effect of bracing was simulated by modeling displacements induced by the brace pads. Simulated clinical indices (Cobb angle, T1−T12 and T4−T12 kyphosis, L1−L5 lordosis, apical vertebral rotation, torsion, rib hump) and vertebral orientations and positions were compared to those measured in the patients' 3D geometries.
Results: Errors in clinical indices were of the same order of magnitude as the uncertainties due to 3D reconstruction; for instance, Cobb angle was simulated with a root mean square error of 5.7°, and rib hump error was 5.6°. Vertebral orientation was simulated with a root mean square error of 4.8° and vertebral position with an error of 2.5 mm.
Conclusions: The methodology proposed here allowed in-depth evaluation of subject-specific simulations, confirming that FEMs of the trunk have the potential to accurately simulate brace action. These promising results provide a basis for ongoing 3D model development, toward the design of more efficient orthoses.

Keywords: Brace; Adolescent idiopathic scoliosis; Simulation; 3D reconstruction; Biplanar radiography

Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional (3D) deviation of the spinal axis [1], which develops in most cases during adolescence and can lead to functional impairment. The scoliotic deformity is usually quantified radiographically using the Cobb angle [2], a two-dimensional (2D) parameter measured in the frontal plane that only suffices for a superficial description of the scoliosis. Surgery is often required at skeletal maturity in the case of severe scoliosis (Cobb angle higher than 45°), whereas conservative treatment (bracing or casting) is preferred when progressive scoliosis is diagnosed earlier (Cobb angle 20°−35°). The challenge of orthotic treatment is to stop or slow down the progression of the spinal curvature prior to skeletal maturity, in order to avoid surgery. Orthotic treatments are widely used for progressive curves; their effectiveness has often been questioned [3,4], but a recent study by Weinstein et al. [5] showed that bracing could

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*Corresponding author. Laboratoire de Biomécanique, Arts et Métiers ParisTech, 151 bd de l'Hôpital, 75013 Paris, France; Tel.: (330) 144246363; fax: (330) 144246366.
E-mail address: c.vergari@gmail.com (C. Vergari).

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significantly reduce scoliosis progression, especially in those patients with a high level of compliance to brace wear.

Low-dose biplanar radiographs can be used in routine clinical practice to assess patient-specific spinal geometry during conservative treatment, allowing better description of the correction in three dimensions [6]. Testing different brace designs in order to optimize correction, however, requires multiple radiographic images; radiation doses can then accumulate over the several years that are often needed for this treatment.

Subject-specific biomechanical models can help to better understand the mechanisms of bracing [7] and ultimately to plan the optimal conservative treatment for a specific subject, thus reducing the number of X-rays needed. Model validation, however, remains a challenge [8] because of the difficulties of obtaining in vivo data to compare to the simulation output. Several studies have used finite-element models (FEMs) for bracing simulation without thoroughly evaluating model consistency [9-11], although attempts to compare simulation and experimental measurements have been performed, generally in a very small number of patients, using 2D or 3D geometric parameters [12-15]. Cobb angle was the main parameter evaluated, whereas lordosis and kyphosis were only evaluated in one study with six patients [15]. Rib hump, frontal shift, and sagittal shift were only assessed in one patient [13]. Vertebral position [12,14] and plane of maximum deformation were evaluated in fewer than four patients [12-14]. Transverse plane parameters (vertebral orientation, apical rotation, torsion) and rib hump are of clinical importance [16], but they have often been neglected in previous studies.

The goal of this study was to propose a method for detailed evaluation of an FEM for simulating bracing effects in AIS patients. For that purpose, simulated key geometric indices (including transverse plane deformity parameters) were compared with those measured in vivo.

Methods

General principle

The evaluation method aimed to compare the simulated correction of the trunk induced by the orthosis with the actual correction as measured on in-brace radiographs. Patient-specific FEMs of the trunk were built from the standing radiograph of the patient's trunk before and during treatment. Orthosis action was simulated in the model by applying local displacements at each pad position, as described below. Simulated clinical indices were then calculated from the deformed FEM shape after simulation. Radiologic indices were measured from the 3D reconstruction of the patient's actual geometry of spine and ribcage within the orthosis. These two sets of clinical indices were then compared to determine the simulation error.

Subjects

Ten AIS patients, nine girls and one boy, with a mean Cobb angle of 25° ± 13° (range 13°–54°) were retrospectively included (Table 1). Low-dose biplanar radiographs (EOS system; EOS imaging, Paris, France) were performed in the standing position both before and during casting (n = 5, P1–P5) or bracing (n = 5, P6–P10); these radiographs were performed as part of clinical routine and were included retrospectively after approval of the local ethics committees. Both braces and casts were adjusted according to the clinician's indications. The delay between the two acquisitions (without and with brace) was 3 months or less (Table 1).

3D Geometry

For each patient, the 3D geometry of the pelvis, spine, and ribcage was reconstructed using previously described techniques [17-22] by experienced users. Briefly, these methods allow the personalization of parametric models of bony structures (vertebrae, ribs, pelvis), based on transversal and longitudinal inferences, to fit the radiographic images of the patient (posteroanterior and lateral). A first reconstruction can be obtained by digitizing specific anatomic landmarks in order to quickly calculate clinical parameters; for the present study, however, each model was manually adjusted to fit the original radiographs for maximum accuracy.

It was hypothesized that vertebrae were not deformed by the orthosis action, implying that the spinal curve correction was due to vertebral displacement and soft tissue deformation alone. Therefore, in order to minimize the reconstruction

Table 1
Characteristics of patients before orthotic treatment. Clinical indices were calculated from the 3D reconstruction without the orthosis.

	Gender	Orthosis type	Time between the two acquisitions	Risser grade	Cobb angle (°)	Lordosis L1–L5 (°)	Kyphosis T1–T12 (°)	Kyphosis T4–T12 (°)	Maximum rib hump (°) (level)	Apical rotation (°)	Torsion Index (°)
P1	F	Cast	Same day	0	13.3	64.4	42.7	33.4	12.4 (T10)	4.6	3.6
P2	F	Cast	Same day	5	24.5	42.3	36.3	40.5	8.2 (T4)	15.2	3.8
P3	F	Cast	2 days	2	53.7	54.3	30.0	9.1	16.1 (T10)	14.8	17.9
P4	F	Cast	1 day	0	39.8	57.3	26.2	2.8	13.4 (T10)	10.1	5.9
P5	M	Cast	1 day	2	12.8	62.0	62.3	44.0	10.0 (T6)	7.3	2.4
P6	F	Brace	2 months	0	17.7	51.8	41.7	39.5	4.8 (T7)	7.7	1.7
P7	F	Brace	Same day	0	15.3	20.6	23.4	34.0	7.6 (T9)	13.8	4.9
P8	F	Brace	3 months	0	27.3	38.1	9.8	6.2	−1.1 (T9)	7.4	9.8
P9	F	Brace	2 months	0	27.6	65.0	36.1	29.0	10.8 (T6)	5.1	4.5
P10	F	Brace	2 months	0	21.3	43.5	24.2	20.8	8.3 (T8)	17.9	2.3

3D, three-dimensional.