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Biomechanics

Biomechanical Simulation of Stresses and Strains Exerted on the Spinal Cord and Nerves During Scoliosis Correction Maneuvers

Juan Henao, M.A.Sc.[a,b,c], Hubert Labelle, MD[b], Pierre-Jean Arnoux, PhD[c,d], Carl-Éric Aubin, PhD, PEng[a,b,c,*]

[a]Department of Mechanical Engineering, Polytechnique Montréal, P.O. Box 6079, Downtown Station, Montreal, Quebec, H3C 3A7, Canada
[b]Research Center, Sainte-Justine University Hospital Center, 3175 Côte Sainte-Catherine Rd, Montreal, Quebec, H3T 1C5, Canada
[c]iLab-Spine (International Laboratory - Spine Imaging and Biomechanics)
[d]Laboratoire de Biomécanique Appliquée, UMRT24 IFFSTAR/ Aix-Marseille University, Bd. P. Dramard, Faculté de Medecine secteur-Nord, France 13916 Marseille cedex 20

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Abstract

Study Design: Biomechanical analysis of the spinal cord and nerves during scoliosis correction maneuvers through numerical simulations.
Objective: To assess the biomechanical effects of scoliosis correction maneuvers and stresses generated on the spinal nervous structures.
Background Data: Important forces are applied during scoliosis correction surgery, which could potentially lead to neurologic complications due to stresses exerted on the nervous structures. The biomechanical impact of the different types of stresses applied on the nervous structures during correction maneuvers is not well understood.
Methods: Three correction techniques were simulated using a hybrid computer modeling approach, personalized to a right thoracic adolescent idiopathic scoliotic case (Cobb angle: 63°): (1) Harrington-type distraction; (2) segmental translation technique; and a (3) segmental rotation−based procedure. A multibody model was used to simulate the kinematics of the instrumentation maneuvers; a second comprehensive finite element model was used to analyze the local stresses and strains on the spinal cord and nerves. Average values of the internal medullar pressure (IMP), shear stresses, nerve compression, and strain were computed over three regions and compared between techniques.
Results: Harrington distraction maneuver generated high stresses and strains over the thoracolumbar region. In the main thoracic region, the segmental translation maneuver technique induced 15% more shear stress, 25% more strain, and 62% lower nerve compression than Harrington distraction maneuver. The segmental rotation−based procedure induced 25% lower shear stresses and 18% more strain, respectively, at the apical level, as well as 72%, 57%, and 7% lower IMP, nerve compression, and strain in the upper thoracic region, compared with Harrington distraction maneuver.
Conclusion: This study quantified the relative stress induced on the spinal cord and spinal nerves for different correction maneuvers using a novel hybrid patient-specific model. Of the three maneuvers studied, the Harrington distraction maneuver induced the most important stresses over the thoracolumbar region.
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Keywords: Scoliosis instrumentation; Spinal cord; Biomechanical impact; Finite element modeling

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*Corresponding author. Department of Mechanical Engineering, Polytechnique Montreal, P.O. Box 6079, Downtown Station, Montreal, Quebec H3C 3A7, Canada. Tel.: 1 (514) 340-4711 ext. 2836; fax: 1 (514) 340-5867.

E-mail address: carl-eric.aubin@polymtl.ca (C.-É. Aubin).

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Introduction

In severe scoliosis, an instrumentation surgery is required in order to correct the spinal deformities and prevent their progression [1,2]. In the early 1960s, Harrington distraction instrumentation surgery was used to correct scoliotic deformations [3] by stretching the curve with a straight rod secured to the spine by hooks placed at the top and bottom of the curve. The main drawbacks of this technique were possible intraoperative neurologic problems [4] and ‘‘flatback’’ syndrome [5] following the procedure. After the introduction of more solid fixation implants such as with pedicle screws, other surgical maneuvers such as rod derotation and vertebra translation were developed in order to provide better three-dimensional (3D) correction [6,7]. The rod derotation technique utilizes a contoured rod inserted on the coronal plane, which is then rotated to the final sagittal position to reduce the curve. A segmental correction by vertebrae translation corrects the spinal deformation by gradually displacing the vertebrae toward the sagittally positioned contoured rods. Nowadays, segmental rotation−based techniques use additional correction maneuvers such as direct vertebral derotation and localized vertebral distraction or compression, to improve the correction in the three anatomical planes. The improvement of such instrumentation technologies allows more powerful means to apply forces and moments to reduce 3D deformities [8,9].

Correction maneuvers transferred to the spine can induce displacement, stresses (internal forces sustained by the tissue, expressed as force per unit of area), and strains (tissue deformation caused by stress, expressed as length in stressed state divided by length in initial unstressed state, in percentage) to the spinal cord and spinal nerves. These stresses and strains could damage the nervous tissues and increase the risk of a neurologic deficit [10]. Excessive traction of the spinal cord or compression of the spinal nerves could lead to a spinal cord dysfunction [11-13].

The biomechanical impact of scoliosis correction maneuvers on the neurologic functions of the spinal cord and spinal nerves is not yet well understood [14]. Few studies have focused on spinal cord injuries related to surgical maneuvers. Only in vitro data have been obtained from traction studies performed on the spinal cord [15,16] and compression tests performed on spinal nerves [17]. To understand the biomechanics of instrumentation maneuvers with the aim of providing safe surgical planning to individual patients, numerical models of the spine and spinal cord could be utilized. Patient-specific finite element models (FEMs) are advanced engineering tools enabling computational comparison of the effects of different surgical procedures on the same virtual spine, with no risk to the patient.

FEMs of the spinal cord have been used to study traumatic contusion to the cord [18-20]. Only one study used a simplified FEM of the spinal cord to assess the effects of degenerative lumbar scoliosis on the nerve roots [21]. Reported models represent only segments of the thoracolumbar spinal cord with 3D geometrical simplifications. For maneuver-related injuries, besides in vitro experimentation, numerical studies have not yet been used [14].

The objective of this study was to biomechanically analyze the stresses and strains developed on the spinal cord and spinal nerves after performing different correction maneuvers using a comprehensive finite element model, to better understand the potential risk to neurologic tissues.

Methods

A novel patient-specific hybrid model was used, comprising a detailed FEM of the spine and spinal cord, used for the calculation of stresses and strains within the bone and soft tissues, coupled with a multibody (kinematic) model used for the computation of the forces exerted on the spine during the various surgical maneuvers. Both models are described below.

Patient-specific FEM of the spine and spinal cord

The reference model was adapted from the Spinal Model for Safety and Surgery, a detailed FEM composed of the spine and spinal cord (Fig. 1) [22-24]. The spine model was initially created from the segmentation of computed tomographic images of a 50th percentile healthy male subject, and was further adapted to represent the patient-specific characteristics of a typical scoliotic case (cf below). The model includes the vertebrae as well as intervertebral discs and principal spinal ligaments over the T1−S1 segment. The spinal cord model was developed using the cadaveric spinal cord cross sections from Kameyama et al. [25]. The model includes the white and gray matters, the pia mater, the denticulate ligament, the dura mater, nervous ganglions, and nerve roots. The gray and white matters were modeled by tetrahedral elements whereas other membranous components were modeled by shell elements. Contact interfaces between spinal cord components and cortical bone (contact surface between dura mater/pia mater, contact surface between spinal canal cortical bone/dura mater) were created to ensure the transmission of loads and motion to the different components of the spinal cord. These loads and motions are physiologically provided by the cerebrospinal fluid as well as epidural fat and ligaments, and the contact interfaces replace the role of these structures in the model. Cortical bone was modeled using rigid shell elements, whereas cancellous bone was not modeled to reduce the number of elements for computational time reduction, as only the bone−spinal cord contact was necessary in this study.

The material properties of the cortical bone, the white and gray matters, as well as the nerve roots were set to the original values of the Spinal Model for Safety and Surgery (Table). For the spinal cord membranes (ie, dura and pia mater as well as the denticulate ligament), the material

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