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Generation of a Patient-Specific Model of Normal Sagittal Alignment of the Spine

Krishna R. Cidambi, MD[a], Diana Glaser, PhD[b], Josh Doan, MSEng[b], Peter O. Newton, MD[b,*]

[a]Department of Orthopedic Surgery, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA, USA
[b]Department of Orthopedics Rady Children's Hospital, 3030 Children's Way, Suite 410, San Diego, CA, USA

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Abstract

Study Design: Mathematical modeling of normal sagittal spinal alignment.
Objective: To create a patient specific 3-dimensional (3D) model of normal adolescent spinal shape and alignment.
Summary of Background Data: Recreating normal sagittal balance is a key goal in spinal deformity surgery. Because of the variation in normal sagittal alignment based on inherent pelvic parameters, it is difficult to know what is normal for a given patient who presents with spinal deformity.
Methods: Simultaneous biplanar 2-dimensional digital radiographs were taken for pediatric patients with no known spinal disease using the EOS system. Three-dimensional reconstructions were produced using sterEOS and imported into custom MATLAB software. The researchers defined relationships to approximate orientations and positions of the vertebral bodies from patients' pelvic incidence (PI). The predicted spinal contour was then calculated to optimize congruence to patients' sagittal T1−sacrum offset, sagittal curve inflection point location, and predicted vertebral body orientations and positions.
Results: A total of 75 patients (26 male and 49 female) were included, mean age 14.5 ± 2.6 years. Baseline measurements were PI 46.7° ± 10.2°, sacral lope 40.2° ± 8.9°, T1−T12 kyphosis 39.8° ± 8.8°, and L1−L5 lordosis −37.1° ± 11.2°. Average difference in vertebral position in the anteroposterior direction between actual spines and their predicted models was 1.2 ± 1.2 mm and varied from an absolute minimum of 0.2 mm (T3) to an absolute maximum of 3.7 mm (L2).
Conclusions: This model uses an adolescent patient's PI to predict the normal sagittal alignment that best matches that patient's native sagittal curve. The model was validated on patients with no spinal deformity; average difference between actual sagittal positions of each vertebra and those predicted by the model was less than 5 mm at each vertebral level. This model may be useful in adolescent scoliotic patients with altered sagittal alignment to determine the magnitude of 3D deformity (compared with predicted normal values) and the completeness of 3D correction.

Keywords: Sagittal contour; Normal sagittal alignment; Spine; Adolescent spine

Introduction

Adolescent idiopathic scoliosis (AIS) results in a complex 3-dimensional (3D) deformity of the spinal column [1]. The goal of surgical treatment of AIS is threefold: prevention of further curve progression, correction of the deformity to achieve a balanced spine in 3 dimensions, and preservation of the corrected position via a stable fusion.

Restoration of the normal sagittal plane contour is recognized as an increasingly important surgical goal, especially with the ability of current pedicle screw fixation to apply significant force to all 3 vertebral columns [2]. Normal alignment in the coronal and transverse planes is easily defined because with the exception of minor perturbations, normal spines are straight in the coronal plane and neutrally rotated in the axial plane. Normal alignment in the sagittal plane is less clear. Because of the variation in normal sagittal alignment based on inherent sagittal pelvic parameters (pelvic incidence [PI]), it is difficult to know what is normal for a given patient with spinal deformity.

Several studies have described the chain of correlation between pelvic and spinal parameters, with large PI correlated

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*Corresponding author. Rady Children's Hospital, 3030 Children's Way, Suite 410, San Diego, CA 92123, USA. Tel.: (858) 966-6789; fax: (858) 966-7494.
E-mail address: pnewton@rchsd.org (P.O. Newton).

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with a large sacral slope and increased lumbar lordosis, and vice versa [3-5]. Additionally predictive equations to estimate lumbar lordosis have been proposed based on multiple linear regression using the following independent variables: sacral slope (SS), T9 spinopelvic inclination, thoracic kyphosis, and PI [3]. The ability of these equations to predict complete sagittal alignment of the spine is limited by poor correlation between kyphosis and lordosis and the selected equation inputs.

Other authors have defined the normal range of radiographic sagittal alignment parameters in asymptomatic populations [6,7]. These studies exhibit a significant range of normal values with respect to sagittal alignment of the spine [8-12]. In addition to normal variation, extrinsic factors such as variation in arm position have been found to affect radiographic assessment of sagittal balance as measured by the sagittal vertical axis (horizontal distance between the C7 vertebral plumbline and the superior posterior corner of the sacrum).

The aim of this study was to generate a patient-specific model of normal adolescent/young adult sagittal alignment of the spine as a function of fixed anatomy not subject to alteration in the setting of scoliosis—in this analysis, the patient's PI.

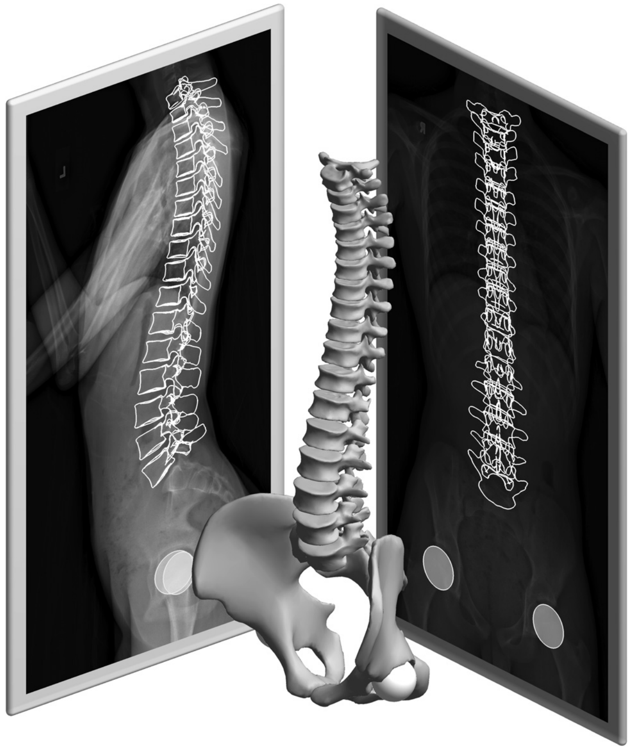

Fig. 1. Three-dimensional spine model generated by sterEOS software.

Material and Methods

Subjects

After the researchers were granted institutional review board approval, they analyzed a total of 75 patients who were referred to a pediatric scoliosis clinic and found to be free of scoliosis and vertebral disease. All patients had less than 10° of spinal curvature or asymmetry.

Image acquisition

All patients were imaged using the EOS system (EOS Imaging, Paris, France). EOS is an upright scanning system that simultaneously acquires coronal and sagittal digital radiographs and permits 3D reconstructions of these images. The system uses orthogonally positioned collimated fan-beam sources and linear detectors (using micromesh gaseous structure technology).

Software reconstruction

Biplanar EOS radiographs were reconstructed and analyzed with sterEOS software. Briefly, the pelvic landmarks (femoral head centers and sacral slope) were defined on coronal and sagittal 2-dimensional images. Next, a digital spline (mathematical function connecting points) was drawn down the center of the patient's spine on both the coronal and sagittal images from T1 to L5. A computer-generated best-fit template of the spine was then automatically overlaid onto the spline representation of the patient's spine. From here, stepwise adjustments of vertebral templates were performed to match them to the patient's vertebrae (Fig. 1).

Model algorithm

Identification of normal patient's spinal contour and model input parameters

Each of the patient's spinal contours was defined by points on the posterior aspect of each vertebral body. This particular location was chosen because it approximates the location of the posterior longitudinal ligament, which was assumed to have constant length. Each spinal contour was normalized by arc length to reduce variability owing to patient size. Four additional parameters were measured for each patient: PI, T1−sacrum offset (T1S), and inflection point height (IPY) and depth (IPX) (Fig. 2). Pelvic incidence is an anatomical parameter independent of the spatial orientation of the pelvis. It is defined as the angle between 1) a line between the midpoint of the sacrum and the midpoint of a line connecting the centers of the femoral heads and 2) a line perpendicular to the sacral end plate. T1−sacrum offset was defined as the horizontal distance between a vertical plumbline dropped from the posterior aspect of the T1 vertebral body and the superior posterior corner of the sacrum. The offset was defined as positive when T1 was anterior to the sacrum. The inflection point (the point of transition from kyphosis to lordosis) was mathematically defined as the point on the spinal contour where the second derivative equaled 0, which is where there was no change in the slope.

Prediction of vertebral locations and orientations

The authors used multiple linear regression to correlate the orientation and posteroanterior position of