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Biomechanical loading of the sacrum in adolescent idiopathic scoliosis

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ABSTRACT

Background: The pelvis maintains an important role in transferring loads from the upper body to the lower extremities and hence contributes to the standing postural balance. Even though changes in spino-pelvic relative alignment are involved in the pathophysiology of scoliosis, the mechanism through which the transferred load between the spine and pelvis is related to the spinal deformity is not well understood.
Methods: A personalized finite element model of the spine and pelvis was constructed for 11 right main thoracic and 23 left thoracolumbar/lumbar adolescent idiopathic scoliosis and 12 asymptomatic controls. The compressive stress distribution on the sacrum endplate was computed. The position of the stress distribution barycenter on the sacrum superior endplate in reference to the central hip vertical axis was projected on the transverse plane and compared between scoliotic subgroups and controls.
Findings: The medio-lateral position of the stress distribution barycenter on the sacrum superior endplate was significantly different between the scoliotic subgroups and controls ($p < 0.05$). The stress distribution barycenter on the sacrum superior endplate was located at the right side of the central hip vertical axis in 82% of the right main thoracic patients and to the left side of the central hip vertical axis in 91% of the left thoracolumbar/lumbar patients.
Interpretation: Analysis of the transferred load to the sacrum provided insight into the biomechanical spino-pelvic interaction in 3D, showing that a thoracolumbar/lumbar scoliotic curve has an increased influence on sacral loads when compared to a main thoracic scoliotic curve.

1. Introduction

In human the pelvis maintains an important role in transferring loads between the lower extremities and spine (Jiang et al., 2006). With this in mind, Dubousset (1994, 1996) introduced the concept of the pelvic vertebra to emphasize the biomechanical role of the sacrum and pelvis relative to the spine. The relative spino-pelvic alignment was believed to ensure postural stability and helps minimize energy expenditure in the bipedal kinematic chain (Berthonnaud et al., 2005, 2009).

To date, most studies have analyzed the geometrical aspects of the spino-pelvic alignment. The relationship between the sacro-pelvic parameters i.e. pelvic incidence (PI), pelvic tilt (PT), and sacral slope (SS), and lumbar parameters has been measured in the static position particularly in the sagittal plane in both asymptomatic (Berthonnaud et al., 2005; Mac-Thiong et al., 2011; Roussouly et al., 2005) and scoliotic subjects (Duval-Beaupère and Cosson, 1992; Labelle et al., 2005; Upasani et al., 2007). The importance of preserving the spino-pelvic relative alignment in scoliosis surgery to protect the patient's postural balance was highlighted in adolescent idiopathic scoliosis (AIS) (Tanguay et al., 2007). Also it was shown that the adaptive spino-pelvic alignment impacts the kinematic of the movement pre- and post-operatively in AIS (Pasha et al., 2010; Skalli et al., 2006), however the biomechanical interaction in terms of the forces transferred between the spine and pelvis was not investigated in scoliotic subgroups.

Several studies focused on the biomechanical loading of the sacrum in isthmic spondylolysis and spondylolisthesis (Natarajan et al., 2003; Sevrain et al., 2012) and reported abnormal stress distribution on the sacrum as well as a relationship between the sacral loading and sacro-pelvic parameters such as sacral slippage and pelvic incidence (Sevrain et al., 2012). However up to now, the biomechanical analysis of scoliosis has mainly focused on the thoracic and lumbar vertebral loading (Clin et al., 2011; Driscoll et al., 2009; Villemure et al., 2002) and not much is known about the differences between mechanical loadings of the sacrum in subjects with different scoliotic types. Since mechanical loading of the sacrum represents the conducted force between the pelvis and the spine, from a biomechanical point of view, study of the sacral loading could be important in the postural evaluation of the AIS. Moreover it can be beneficial in further evaluation of the longitudinal changes at the lumbosacral junction in patients with AIS.

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This paper aimed to analyze and compare the load patterns transferred to the sacrum based on the morphology and relative orientation of the sacrum and spine between controls and scoliotic subjects with two different curve types.

2. Methods

2.1. Subjects

23 scoliotic patients with a left thoraco-lumbar/lumbar (TL/L) curve and 11 with a right main thoracic (MT) curve were selected randomly from our institution database of patients diagnosed with AIS. Inclusion criteria consisted of a diagnosis of AIS with no previous spine surgery, a Cobb angle exceeding 20° for the main thoracic or lumbar scoliosis, absence of a concomitant spinal pathology such as a spondylolisthesis, and no leg length discrepancy greater than 1 cm. In addition, 12 asymptomatic control subjects, examined by a spine surgeon, with no history of spinal, hip or lower limb disorder were included in this study. All participants were female adolescents. The research proposal was accepted by the ethic committee of our institution.

2.2. Measurement of the patient's morphological parameters

The 3-dimensional reconstruction of the spine, pelvis, ribcage, and the position of the femoral heads was derived from digitized landmarks on the postero-anterior and lateral X-rays using a 3D reconstruction and self-calibration method (Cheriet et al., 2002; Kadoury et al., 2007a, 2007b). A detailed atlas of the spine and pelvis along with a freeform deformation technique were used to create a comprehensive geometry of the spine, pelvis, and ribcage (Cheriet et al., 2002; Kadoury et al., 2007a, 2007b). In this self-calibration technique the calibration object was eliminated and instead the sets of matched anatomical landmarks on the bi-planar X-ray images were used to calibrate the X-ray images.

In applying the self-calibration technique, an average error of 1.2 mm (SD 0.8 mm) was calculated on the vertebral body and 1.6 mm (SD 1.1 mm) on the pedicles of the 3D reconstructed images. The maximum error in measurement of the pelvic sagittal parameters is $0.99 \pm 1.10°$ and the accuracy of the femoral head axis alignment in frontal plane was reported at $0.44 \pm 0.46°$ (Kadoury et al., 2007a). Maximum error of 5 mm was calculated for the pelvic body landmarks. Average variations of 1° and 7° were reported in the calculation of the spinal curves' angles in the coronal and sagittal planes respectively when results from the 3D reconstruction were compared to the 2D measurements on the radiographs by clinicians and the direct linear transformation (DLT) technique (Delorme et al., 2003).

The spinal parameters (thoracic and lumbar Cobb angles, kyphosis, and lordosis) and sacro-pelvic parameters i.e. PI, PT, and SS were determined. These pelvic parameters are presented in Fig. 1. Kyphosis and lordosis angles were computed between T4–T12 and L1–S1 respectively. The 3D coordinates of the center of the femoral heads were determined using the 3D reconstruction method described above. The central hip vertical axis (CHVA) was defined as the vertical line passing through the midpoint of the line joining the center of the femoral heads and was used as the reference axis (Sangole et al., 2010).

2.3. Finite element modeling and simulation

An osseo-ligamentous finite element (FE) model of the spine from T1 to S1, ribcage, and pelvis was constructed using ANSYS 11.0 FE package (ANSYS Inc., Canonsburg, PA, USA). A detailed version of this model is described elsewhere and the main components are summarized here (Clin et al., 2011). 3D elastic beam elements were used to present the vertebrae, intervertebral disc, ribs, sternum and rib cartilages. Intercostal ligaments were modeled with tension-only spring elements while zygapophyseal joints were modeled using non-linear contact and shell elements. The abdominal cavity was presented by 3D elastic beam elements. The nodes of the ribcage, pelvis, and vertebrae were interpolated to create the equivalent beam elements of the abdominal cavity. A model of the trunk surface and external soft tissues was approximated by the 3D coordinates of these interpolated nodes. The nonlinear hexahedral solid elements were created to approximately model the external soft tissues of the trunk (Clin et al., 2011).

The mechanical properties of different components of the model were derived from literature (Aubin et al., 1995; Descrimes et al., 1995). The Young moduli of different components of the model are presented in Table 1.

The translation of the first thoracic vertebrae in the transverse plane was fixed but movement was allowed in the Z direction. The pelvis was fixed in space. The boundary conditions as presented in the manuscript were applied on the FE model of the trunk to simulate the behavior of the isolated torso model. Fig. 2 shows the generated finite element model of the spine, rib cage, and pelvis.

The weight of the trunk slices, head, neck, and arms was determined as a percentage of the total body weight. The position of the center of mass (CoM) of each trunk slice was set at the center of each vertebral body in the frontal plane. In the sagittal plane the CoM of the trunk slices at the level of each vertebra was determined from literature (Liu et al., 1971; Pearsall et al., 1994, 1996). The weight of each trunk slice as a percentage of the whole body weight is presented in Table 2. A rigid beam was used to connect the CoM of each trunk slice to the center of the vertebrae. The weight of the head and neck was associated with that of the

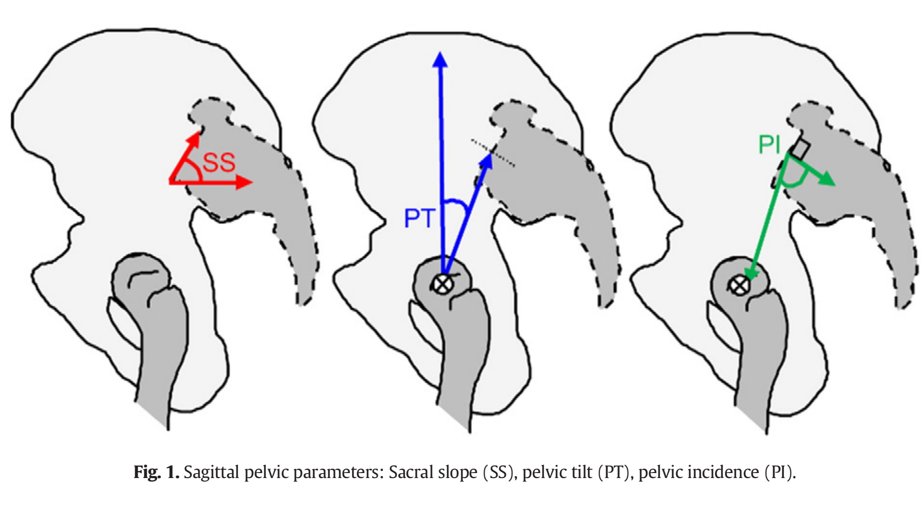

Fig. 1. Sagittal pelvic parameters: Sacral slope (SS), pelvic tilt (PT), pelvic incidence (PI).