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The biomechanical effects of spinal fusion on the sacral loading in adolescent idiopathic scoliosis

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ABSTRACT

Background: Posterior spinal surgical correction is performed to correct spinal deformities in adolescent idiopathic scoliosis. Althoughthe relative spino-pelvic alignment changes after spinal surgery, pelvis remains unfused in idiopathic scoliosis surgery. The impact of the spinal fusion on the transferred load to the pelvis via sacrum is not documented in the scoliotic subgroups.
Method: Bi-planar radiographs of 9 scoliotic subjects before and in average 16 months after spinal instrumentation surgery, and 12 controls were selected retrospectively. Patient-specific 3D reconstruction and finite element models of the spine, ribcage, and pelvis were developed. Spinal parameters (Cobb angles, kyphosis, lordosis), sacro-pelvic parameters (pelvic incidence, pelvic tilt, sacral slope), frontal and sagittal balances, the position of the trunk center of mass, and the centroid of the stress distribution on the sacrum superior endplate were measured and computed before operation and in the last follow-up.
Findings: The position of the stress distribution centroid on the sacrum superior endplate with respect to the central hip vertical axis was significantly different between pre-operative and post-operative patients $p < 0.05$. The distance between the anterior–posterior position of the trunk center of mass and thecenter of pressure on the superior sacral endplate significantly decreased after the spinal surgery $p < 0.05$.
Interpretation: The impact of the scoliosis spinal fusion on the transferred load between the spine and pelvis was evaluated. The biomechanical loading of the sacrum endplate was related to the post-operative postural balance and compensatory changes in the spino-pelvic alignment after scoliosis surgery.

1. Introduction

Posterior spinal instrumentation and fusion (PSIF) aims to correct and stabilize the spinal deformity in severe cases of scoliosis until fusion occurs (Bridwell et al., 2002; Moen and Nachemson, 1999). Although the clinical impact of the spinal fusion on the geometrical parameters of the spine and pelvis has been studied previously (Masso and Gorton, 2000; Tanguay et al., 2007) the effects of the spinal surgery on the biomechanical loading of the distal un-fused vertebrae are not well documented. More specifically the biomechanical loading of the sacrum, which affects the conducted force between the spine and lower extremities and hence contributes to the standing postural equilibrium (Jiang et al., 2006) is not closely investigated in adolescent idiopathic scoliosis (AIS) subgroups post-operatively. The asymmetrical loading of the spinal vertebrae (Stokes, 2007) is shown to be associated with curve progression, which emphasizes on the importance of the considering the vertebral loading of the unfused spine in post-surgical evaluation of the patients.

Since the introduction of the "pelvic vertebra" in 1994 (Dubousset, 1994), pre- and post-operative spino-pelvic alignment in scoliosis has become the subject of many studies (Legaye et al., 1998; Pasha et al., 2010; Pasha et al., 2014a; Qiu et al., 2013; Roussouly, et al., 2013). Changes in pelvic alignment and spino-pelvic kinematic interaction were highlighted after spinal surgical correction in scoliosis (Skalli et al., 2006; Tanguay et al., 2007; Yang et al., 2015). The importance of considering the pelvic sagittal alignment with respect to the spine particularly the lumbar lordosis in AIS surgical planning was underlined (Johnson et al., 2012; Roussouly et al., 2013; Tanguay et al., 2007). However the transferred load to the pelvis through sacrum characterized by the compressive stress on the sacrum in post-surgical AIS that may impact the long-term spino-pelvic alignment is still to be investigated.

Despite the body of literature examining post-surgical spino-pelvic analysis in AIS, it is not clear to what extent the spinal surgery impacts the biomechanical loading of the pelvis and lower limbs in post-operative AIS subgroups. In order to answer this question the specific objective of the current study was to compute and compare the compressive

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stress on the superior sacral endplate in pre- and post-operative scoliotic subjects with different curve patterns and also compare it to a group of asymptomatic controls using a comprehensive osseo-ligamentous finite element model of the spine and pelvis (Clin et al., 2011). It was hypothesized that even though sacrum remains unfused in AIS spinal surgery the biomechanical loading of the sacrum changes significantly after PSIF in AIS subgroups and becomes more similar to the ones in controls in a balanced spino-pelvic alignment after the surgical correction of the spine.

2. Methods

2.1. Subjects

The ethical approval was obtained from the ethical committee of the hospital and the affiliated research institution for this research study. A total number of 9 AIS female subjects (age range [14, 17], average 15 years, SD: 2.4, average weight 50.1 kg, SD 6.2) who had undergone a PSIF between 2006 and 2010 were randomly and retrospectively selected from the database of our institution. This sample size provided 80% statistical power for a paired analysis between the pre- and post-operative patients. All- pedicle- screw construct was used for all the patients except for one who was treated with a hybrid construct (screws and a distal hook). The number of fused vertebrae varied between 6 and 14 vetebrae. No post-operative instrumentation failure or surgical complications during an average follow-up of 16 months [12–18 months, SD: 3] was reported in the studied group. The medical chart and pre- and post-operative bi-planar radiographs of the patients were consulted. A total number of 5 patients had right main thoracic deformity (RT), Cobb angle range [43°, 77°] and 4 patients had right thoracic (RT) [55°, 68°] and left lumbar (LL) [74°, 97°] deformities. The radiographic images of 12 age- and sex-matched asymptomatic female adolescent subjects [age 11–18 years average 14.3, SD 4.0, average weight 54.8, SD 8.3] with no history of spinal disease were examined by an orthopedic surgeon and were added as the control group.

2.2. 3D reconstruction technique and anatomical measurements

A self-calibration technique was used to generate the weight-bearing 3D reconstructions of the spine, rib cage, and pelvis of the cohort from their bi-planar X-rays before and after surgery using the technique explained by Kadoury et al. (2007) (Fig. 1-A and Fig. 1-B). The reconstruction method consisted of identifying a limited number of points on the radiographs (14 nodes per vertebra, 11 nodes per rib, and 24 nodes on the pelvis) and using a detailed atlas of the spine and pelvis along with a free form morphing algorithm to create the detailed skeletal geometry of the spine, ribcage, and pelvis (Cheriet et al., 2002; Delorme et al., 2003; Kadoury et al., 2007). In the self-calibration process the retro-projection errors of the anatomical landmarks were minimized by changing the radiological setup. The new radiological setup was determined by changing the geometrical parameters of the radiographic system during a non-linear optimization process. The self-calibration and reconstruction methods are described in farther detail in Kadoury et al. (2007). In order to determine the accuracy of the 3D reconstruction model using the self-calibration technique all the 3D measurements were compared to a previously verified calibration and 3D reconstruction technique (Cheriet et al., 2002 and 2007). The 3D reconstructions were generated for 60 patients using both methods and were statistically compared. The average errors in the 3D reconstruction of the vertebral body, originated from the self-calibration technique, were (1.2 mm, S.D. 0.8 mm) and vertebral pedicles (1.6 mm, S.D. 1.1 mm). The accuracy of the bi-femoral head axis alignment in the frontal plane was 0.44°, S.D. 0.46°. The maximum error in measurement of the pelvic sagittal parameters was 0.99°, S.D. 1.10° (Kadoury et al., 2007). A maximum error of 7° was reported in 2D coronal and sagittal spinal curves measurements using the 3D model when compared to the 2D clinical measurements on the X-ray images (Delorme et al., 2003).

An analytical method was used to measure the spinal curvatures in the frontal and sagittal planes (Stokes, 1994) as shown in Fig. 1-B and

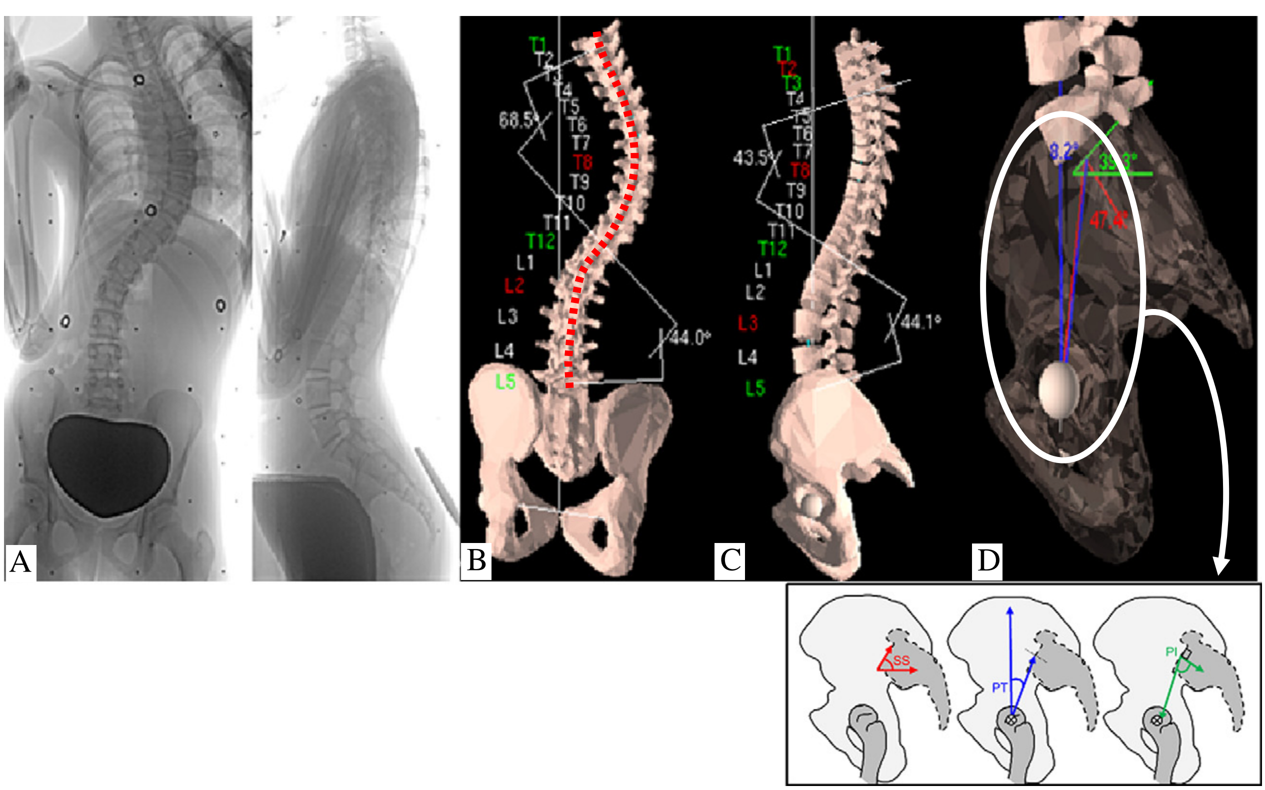

Fig. 1. A) Bi-planar X-rays. An analytical method was used to measure B) thoracic and lumbar Cobb angles, C) kyphosis (T4–T12), and lordosis (L1–S1) from the 3D reconstruction of the spine. The dashed line in Fig. 1-B is the spline connecting the vertebral centroids. D) Sacro-pelvic parameters in the sagittal plane: Sacral slope (SS), pelvic tilt (PT), and pelvic incidence (PI).