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Current Concepts in Pathogenesis and Biomechanics of Adolescent Idiopathic Scoliosis

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ABSTRACT

Considerable progress has been made in the past two decades in understanding the pathogenesis and biomechanics of adolescent idiopathic scoliosis (AIS). Biplanar asymmetry has long been considered as the essential of idiopathic scoliosis. Median plane asymmetry is crucial for progression of idiopathic scoliosis.The presence of thoracic lordosis or hypokyphosis has been emphasized in the development of AIS. The changes in the cartilaginous endplate and the intervertebral disc are key factors in the progression of scoliosis and the way the curve responds to different therapeutic regimens. This article aims to analyze the current concepts in pathogenesis and biomechanics of AIS as well as to describe conservative and surgical treatment biomechanics. Biomechanical differences between AIS and degenerative scoliosis are also analyzed.

KEY WORDS: biomechanics, adolescent idiopathic scoliosis, classification, rotational imbalance

Introduction

Idiopathic scoliosis is classified into three types according to the age of onset: infantile (0-3 years old), juvenile (4-9 years old), and adolescent (10 years old to skeletal maturity) [1-3] with adolescent idiopathic scoliosis (AIS) being the most frequent type. With the general belief that AIS is a multifactorial disorder, it is likely that its pathogenesis involves different degrees of interaction between different factors in linear and summation causality [4].

Classification systems of AIS include Ponseti, King, Lenke, Peking Union Medical College, and Three-dimensional classification. Nowadays, Lenke's classification [5] is the most commonly. The six curve types of Lenke's classification are summarized in Table 1.

This article aims to analyze the current concepts in pathogenesis and biomechanics of AIS as well as to describe conservative and surgical treatment biomechanics. Biomechanical differences between AIS and degenerative scoliosis are also analyzed.

Biomechanics of AIS

Biplanar asymmetry has long been considered as the essential of idiopathic scoliosis [6]. Median plane asymmetry is crucial for progression of idiopathic scoliosis.

The presence of thoracic lordosis or hypokyphosis has been emphasized in the development of AIS [6]. Lordosis can be defined as the deviation of the scoliotic spine that occurs with axial rotation of the vertebral bodies towards the convexity of the lateral curve,

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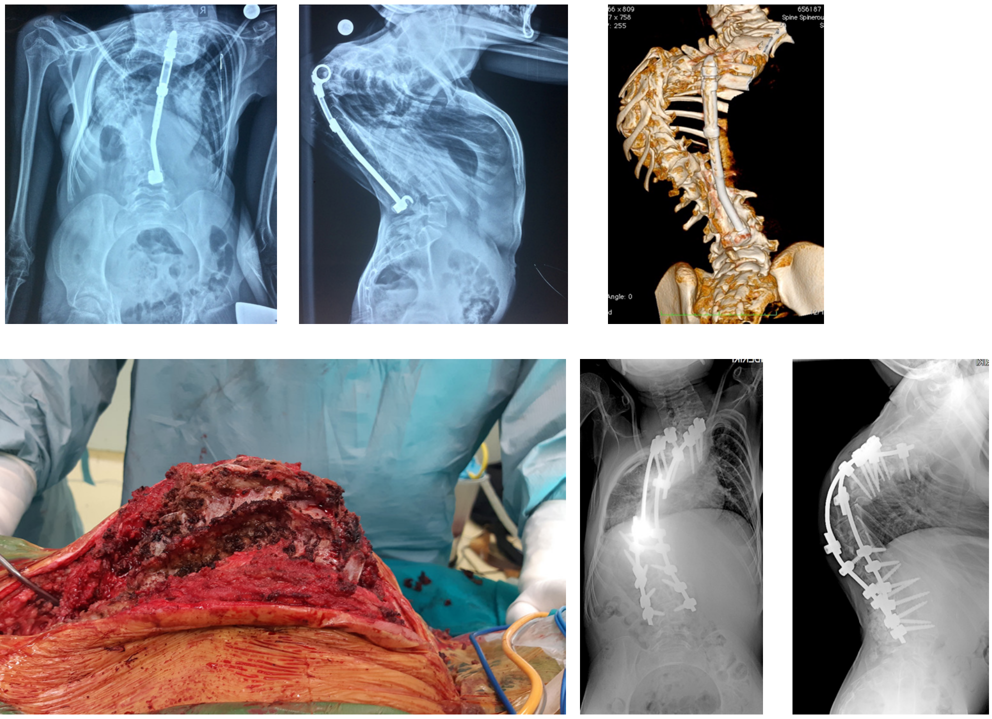

Figure 1. *A simple mathematical model for the investigation of the efficiency of different loads to correct a scoliotic curve. Taken from: White AA, Panjabi MM. Clinical biomechanics of the spine. JB Lippincot Co. Philadelphia, Toronto, 1990.*

producing a three-dimensional deformity in which the vertebral bodies form a greater arc than the posterior structures.

Median plane asymmetry is characterized by increased anterior vertebral height at the apex of the curve and posterior end-plate irregularity [7]. The vertebral bodies have a faster growing rate than the posterior elements [8]. This discrepancy in growth between the anterior and posterior elements is of unknown etiology and results primarily in lordosis. The slower growth of the posterior elements impedes the vertebral bodies from increasing in height, forcing them to become distorted in order to create space for themselves. This, in turns, results in rotational lordosis [7].

Regarding the pathomechanism of AIS, the concept of a primary skeletal change which affects the sagittal plane of the spine with anterior increments and posterior decrements of vertebral growth has been adopted. In a study of 2003 [8], after applying whole spine MRI in female patients with AIS, the investigators concluded that the scoliotic spines have longer vertebral bodies, shorter pedicles, and larger interpedicular distance than the normal spine. It was also noticed that the ratio of anteroposterior vertebral body components correlated significantly with the severity of scoliosis. The authors, after comparing age-matched females with scoliotic or normal spines, suggested that the longitudinal growth of the vertebral bodies is faster and disproportionate in scoliotic spines and mainly occurs by endochondral ossification. On the other hand, the circumferential growth by membranous ossification is slower in females with AIS when compared with normal controls in both vertebral bodies and pedicles.

According to a study of 2011 [9], the direction of the spinal curve in idiopathic scoliosis is determined by the rotational pattern that the spine exhibits at the time of onset. The predominance of right sidedthoracic curves in adolescent idiopathic scoliosis and left-sided curves in infantile idiopathic scoliosis can be explained by the observed patterns of vertebral rotation that preexist at the corresponding age. The rotational pattern in nonscoliotic adult spines that corresponds to the most common curve types of AIS, i.e. the right sidedthoracic curve, is predominantly seen in females [10].

The vertical position of the spine results in reduced anterior shear forces as compared to the horizontally positioned (quadruped) spine. In case of a backwardly declined vertebra, e.g. during growth, anterior shear

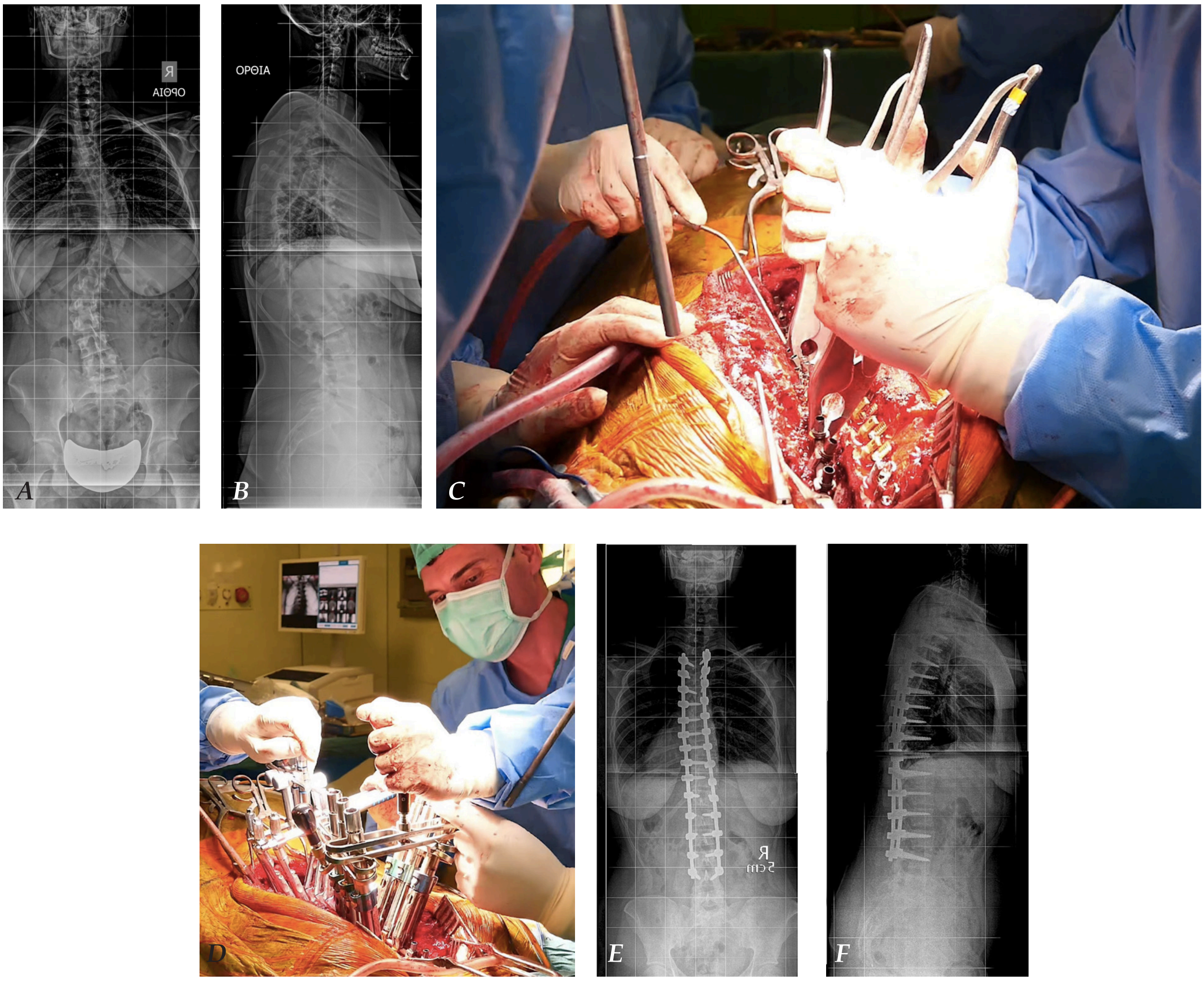

Figure 2. *Anteroposterior (A) and lateral (B) x-rays of a 16 year-old girl with AIS. Her right thoracic curve measured 58° and her left lumbar curve 50°. Intraoperative pictures showing three dimensional deformity correction with rod derotation maneuver (C) and apical vertebra derotation (D) using the VCM system (Medtronic, Memphis, USA). One year after posterior spinal fusion from T4 to L3, anteroposterior (E) and lateral (F) x-rays revealed a right thoracic curve of 6° and a left lumbar curve of 0°.*

forces are reduced further and may turn into dorsal loads [11]. In this case, a slight preexisting vertebral rotation may be enhanced resulting in a progressive deformation of the backward inclined growing spine because of the Hueter-Volkmann principle. Facet joints contribute significantly to rotational stability of the spine. In the upright position, anterior shear forces diminish and may even turn into dorsally directed forces. When the anterior shear forces become negative, the stabilizing mechanism of facet joints is diminished androtational imbalance must be counteracted by internal forces (strains). Inevitably, this will result to asymmetric loading in the transverse plane of the vertebrae, intervertebral discs, and attached ligaments, enhancing slight pre-existing asymmetries [11].

The intervertebral disc is also involved in biomechanics of idiopathic scoliosis. The intervertebral disc becomes significantly and irreversibly wedged in patients with progressive scoliosis [12]. However, intervertebral disc wedging is not considered a primary factor but a contributing variable to the deformity [13]. It is very likely that the changes in the cartilaginous endplate and the intervertebral disc are key factors in the progression of scoliosis and the way the curve responds to different therapeutic regimens [14]. An increased torsional rigidity of the intervertebral disc

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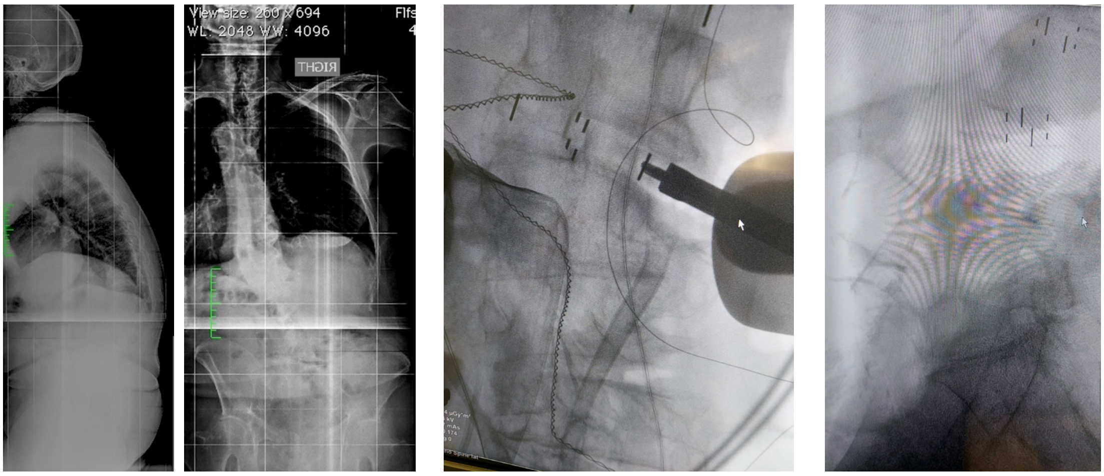

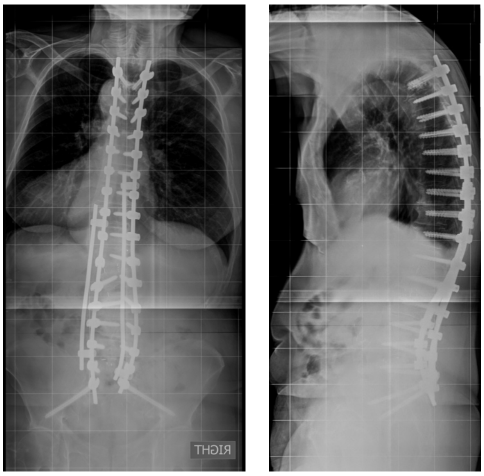

Figure 3. *Anteroposterior (A) and lateral (B) x-rays of a 72 year-old male with degenerative kyphoscoliosis and significant coronal and sagittal imbalance. His right lumbar curve measured 30°, his left thoracolumbar curve 25°,andhis focal thoracolumbar junction kyphosis 25°. The patient underwent a staged procedure including a first-stage direct lateral interbody fusion at the apex of the deformity (L1-2 and L2-3) with release of the anterior longitudinal ligament for better kyphosis correction (C, D) and a second stage posterior spinal fusion from T3 to pelvis with a four-rod construct (E, F)*

throughout growth that favors the progression of early scoliotic curves has been reported [15].

In 2006 [16], 70 children with a scoliotic curve were reviewed in order to investigate whether the deformation of the intervertebral disc contributes to the progression of idiopathic scoliosis. The authors concluded that the adjacent to the apical vertebra intervertebral disc wedging is a more important parameter in the progression of idiopathic scoliosis than the apical vertebral wedging, which appears later when the Cobb angle has already increased. Idiopathic scoliosis is associated with distinctive intravertebral deformity, with smaller pedicles on the concave side and a shift of the dural sac toward the concavity [17]. These findings highlight the importance of the intervertebral disc in idiopathic scoliosis pathogenesis and biomechanics.

Biomechanics of treatment

The main goal of treatment is to return the spine to a normal configuration. Several techniques with correcting loads have been proposed in order to correct the deformities in idiopathic scoliosis with either surgical or non-surgical measures.

Conservative treatment of idiopathic scoliosis involves stabilization of the unstable spine and transmission of forces that could restore the natural geometric configuration.

Bracing

A simple mathematical model proposed for the investigation of the efficiency of different loads to correct a scoliotic curve is composed by 2 rigid links (AC and AB) connected at C by way of a torsional spring in the coronal plane (Fig. 1). When the spine is subjected to a transverse force (F) at point C, reactive forces equal half of the force applied (F/2) are taken up at points A and B (Fig. 1C). The corrective bending moments created at the disc spaces allow angular correction of the

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TABLE 1.

Curve types according to Lenke's classification

Curve Type	Curve Name	Proximal Thoracic (PT)	Main Thoracic (MT)	Thoracolumbar/ Lumbar (TL/L)
Type 1	MT	-	Structural	-
Type 2	Double Thoracic	Structural	Structural	-
Type 3	Double Major	-	Structural	Structural
Type 4	Triple Major	Structural	Structural	Structural
Type 5	TL/L	-	-	Structural
Type 6	TL/L-MT	-	Structural	Structural

curve in the frontal plane. The corrective bending moment at the apex can be calculated by multiplying the half of the transverse force (F) applied by the perpendicular distance to the apex of the curve (D). The corrective bending moment decreases as the perpendicular distance to the apex, and thus, the deformity increases. This type of loading is utilized in conservative management of scoliosis with bracing. Scoliotic spine response to brace treatment is determined by two factors: 1) the vertebrae remodeling capability in accordance with the Hueter-Volkmann principle and 2) the capability of the viscoelastic structures to react to the imposed actions appropriately. No mechanical action can produce the remodeling process without an adequate response from the viscoelastic structures involved. These structures, and in particular the intervertebral disks, can modify the areas subject to tension concentration by absorbing and by redistributing the actions of the brace on a singular vertebra [18].

Similar to transverse loading, when axial loading is applied at the cephalad and caudal end vertebrae (points A and B in Fig. 1B), corrective bending moments are created at the various disc spaces correcting the spine deformity. The corrective bending moment created at the apex of the curve equals the axial force (F) multiplied by the perpendicular distance to the apex of the curve (D).

Surgical

Segmental fixation with hooks has been gradually replaced by pedicle screw fixation which, theoretically, provides stronger biomechanical fixation and allows improved three-dimensional correction and maintenance of the spinal deformity [19-21]. In a comparative study [22] of different implant densities, the difference in the density of screws did not lead to significant difference as far as it concerns the main thoracic Cobb angle and the main thoracic apical axial vertebral rotation. There were also on average 13% more pedicle screws and 30% more bilaterally placed pedicle screws in the higher versus lower density group. The authors concluded that with the same fusion levels, lower density screws allowed achieving similar deformity correction and it was more likely to have lower screw-vertebra loads. During the last years, the three dimensional deformity correction with segmental pedicle screw fixation has gained supporters, since the rod derotation maneuver enables a powerful coronal and sagittal plane correction as well as rotational correction in the axial plane,replacing distraction or supplementing it as current method of correction (Fig. 2).

The basic biomechanics of a pedicle screw are based on the following parameters:

- The outer diameter of the screw determines the pullout strength, while the inner diameter the fatigue strength
- When inserting a pedicle screw, the dorsal cortex of the spine should not be violated and the screws on each side should converge and be of adequate length

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- Rotational stability can be improved by adding transverse connectors [23]

Pedicle screw is considered biomechanically advantageous compared to the hybrid hook-screw system, since the pedicle is the hardest part of the vertebra [24]. In a retrospective comparative study of 58 patients with AIS treated with either pedicle screw or hybrid instrumentation, Kim et al. [25] found that immediately after surgery average major curve correction was 70% for the pedicle screw group and 56% for the hybrid group. Significant difference between the 2 groups was also noted at 2-year follow-up, with the all-pedicle screw construct achieving 65% of correction and hybrid instrumentation 46%. In another comparative study of patients with AIS treated with pedicle screw or hybrid instrumentation with a mean follow-up of 41 months [24], the authors demonstrated the ability of the all pedicle screw construct to fulfill the long-term traditional goal of scoliosis surgery: maximum coronal plane correction and prevention of deformity progression while maintaining balance. In the sagittal plane, although both systems achieved similar correction of lumbar lordosis, the hybrid construct was found to have less kyphogenic potential to the thoracic spine than the pedicle screw system.

Biomechanical differences between AIS and degenerative scoliosis

In contrast to AIS, in which the main deformity component is rotational lordosis, degenerative scoliosis has a rotational and a kyphotic component. The rotational deformations are manifestations of an asymmetrical load or a rotatory load applied to a spinal segment. The application of a rotatory or torsional load to the spine can cause the spinal segments above the unstable segment to rotate in an opposite direction to those below the unstable segment. At the thoracolumbar spine, the disc degenerative changes are directly related to the development and progression of scoliotic curves (Fig. 3).

In contrast to AIS, in which the intervertebral disc is not a primary factor but consists a contributing variable to the deformity, in the degenerative form of scoliosis the changes of the intervertebral disc play an important role in the development of spinal deformity. In 1995 [26] it was suggested that flexion-extension, lateral bending and axial rotation decrease on an average of 23%, 31% and 25%, respectively for patients more than 50 years of age compared with patients 20-29 years of age. By aging, the intervertebral disc progressively loses its viscoelastic properties which results in decreased shock absorption and uneven stress distribution [27]. The dehydration of the nucleus pulposus results in reduced intradiscal pressure which along with the thinning of the cortical bone may cause anterior wedging of the vertebral body and kyphotic deformity.

Conclusion

Considerable progress has been made in the past two decades in understanding the pathogenesis and biomechanics of AIS. Biplanar asymmetry has long been considered as the essential of idiopathic scoliosis. Median plane asymmetry is crucial for progression of idiopathic scoliosis. The changes in the cartilaginous endplate and the intervertebral disc are key factors in the progression of scoliosis and the way the curve responds to different therapeutic regimens.

Conflict of interest

The authors declare no conflicts of interest.

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