Frontal and sagittal imbalance in patients with adolescent idiopathic deformity

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Abstract: The human spinal column underwent many significant changes over the 4.5 million years of our ancestral bipedalism. The main change, however, came with acquiring multiple curvatures in the sagittal plane. This alteration seems to have exposed a weakness in our body’s keystone and made us susceptible to thus far unbeknown problems of the spine because it has been noted that idiopathic scoliosis has not been observed in other primates. Adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity of the spine causing an imbalance of the trunk as it increases in magnitude. A scoliotic curve comprises three components, the coronal, sagittal, and axial so that each curve can affect the global balance of the body differently. Patients with significant scoliotic deformities often find themselves at a biomechanical disadvantage when it comes to energy expenditure and keeping an upright stance. The pioneers of scoliosis research recognized the need for describing and quantifying deformity to better understand it, so they first translated clinical measurements to radiographs and built from there. The development of concepts like defining a curve by its end vertebrae and measuring its magnitude, assessing global spinal balance, describing the stable zone, and pinpointing the stable vertebra all followed suit. The importance of sagittal balance and restoring sagittal parameters during treatment was emphasized. In a quest to bring order to chaos, some tried to classify various scoliotic curve types. These classifications helped steer treatment decisions but were found lacking in many aspects. So far, a widely accepted three-dimensional classification of scoliosis still does not exist. This review aims to provide the reader with an overview of the development of balance and imbalance concepts in scoliosis.

Keywords: Adolescent; kyphosis; lordosis; scoliosis; spine

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Introduction

The term scoliosis, derived from the Greek word meaning “crooked”, was first used as regarding spinal deformities by Hippocrates (460–370 BC) (1,2). However, in his works, this term is given a generic meaning, referring to almost any type of spinal curvature. One of his successors, Galen of Pergamon (129–210 AD) commented on Hippocrates’ flawed use of the term, and described four types of spinal deformities—kyphosis when the spine moves backward, lordosis when propelled forward, scoliosis as it shifts to the side and succussion, a situation without any deformity but with movement of the intervertebral articulations (3). So, it is Galen who is credited for the first use of this term as it is used today.

Modern orthopedic surgery defines scoliosis as a lateral...
curvature of the spine greater than 10° measured on a posteroanterior (PA) radiograph, a method introduced by Cobb in 1948 (4). This is a complex deformity, comprising changes in all three anatomical planes: a lateral shift in the coronal, straightening or bowing in the sagittal, and rotation around the vertebral axis in the axial plane (5). The most significant changes are in the apex of the curve, and as the deformity progresses, it brings upon structural changes of the vertebrae and the rib cage. This three-dimensional (3D) spinal deformity also invariably influences the spinopelvic alignment.

Adolescent idiopathic scoliosis (AIS) is by far the most common type of scoliosis, with a prevalence of 2–3% in children aged 10 to 16 years, with girls bearing a larger risk for progression, by a ratio of 3.6:1 (6). Various etiologies for AIS have been proposed in the literature, with one of the theories focusing on a deficit in postural balance which could result in scoliosis (7-11). Herman et al. found a cause of AIS in a sensory rearrangement of the motor system on the representation of the body in space (12). Failure of determining the center of pressure (CoP) position concerning the body’s center of mass (CoM) due to a sensory integration disorder could cause balance maladjustment in AIS (13). Beaulieu et al. confirmed this sensory integration disorder in the basis of scoliosis, and assumed a two-staged process of spinal deformity development: in the initial stage, a small curve is caused by a defect of the neuromuscular and sensorimotor system, while in the second stage the increase of the curve and neurological dysfunction disturb the ability to recalibrate the CoP position in relation to CoM, namely postural balance (14).

Problems of global balance affect patients with every type of scoliosis, from the mildest to the most difficult cases, untreated ones, the ones undergoing brace treatment, as well as those who have had surgery for their deformity. The purpose of this article is to summarize and reevaluate today’s knowledge of the issues of spinal balance in AIS.

**Frontal (IM) balance in AIS**

The spinal column is the keystone of the body, and deformations that cause it to fall out of balance-decompensate, do so to the entire trunk. Clinically, the examiner can assess spinal balance by dropping a plumb line from the midpoint of the occiput and measure its distance from the gluteal crease. Rudicel and Renshaw used this method on a standing radiograph by measuring the horizontal distance between a vertical line from the midpoint of the occiput or the highest depicted vertebra, and the other from the midline of the sacrum (15). Floman et al. observed that many patients exhibit satisfactory alignment of the head over the pelvis yet show a significant shift of the trunk away from the midline (16). Harrington devised the premise of the stable zone which is supposed to contain the lower instrumented vertebra, defined by two vertical lines drawn through the lumbosacral facets (17). King et al. worked to improve pinpointing the accuracy of the stable zone’s location and instituted a reference line called the central sacral line (CSL), a single vertical line from the midline of the sacrum perpendicular to the iliac crests (18). The vertebra most closely bisected by this line is considered the stable vertebra. The authors emphasized the importance of basing this line on a horizontal pelvis, so any leg length discrepancy always needs to be addressed before taking the radiograph (18).

There is no uniformity in reporting spinal compensation/decompensation in the literature (19). Some authors use the position of the head, while others rely on the position of the thorax over the pelvis (16,18,20-27). According to the Scoliosis Research Society (SRS), “compensation” is the vertical alignment of the center of C7 vertebra over the midpoint of the sacral plateau in the coronal plane. This alignment is designated as coronal (frontal) balance (CB), and it refers to the position of the head with the pelvis (Figure 1) (29). Consequently, decompensation in AIS is a deviation of the CB axis from normal, usually for more than 2.0 centimeters. Measuring the position of the thorax with the pelvis, on the other hand, can be done in two ways. One, invented by Floman et al. using the lateral trunk shift (LTS), measured as the horizontal distance from the center of the pelvis to a point bisecting the line between the edges of the most peripherally displaced ribs (Figure 2) (16,25). The other method, thoracic apical vertebral translation (tAVT), is performed by measuring the distance from the center of the apical vertebra in the thoracic spine to a vertical dropped from the C7 vertebra (21,22,30). The lumbar spine can also be the cause of a loss of balance, so lumbar apical vertebral translation (lAVT) is measured as the distance from the center of the lumbar apical vertebra to the center sacral line (30). Richards found that the trunk shift was more accurate in anticipating spinal balance than the C7 alignment with the sacrum (25).

Matters of the frontal balance (FB) of the spine came into the spotlight with the advent of surgical treatment for scoliosis, as surgeons tried to decide on which areas to include in the fusion, a matter still heavily debated.
today. Surgical treatment of AIS strives to achieve fusion in the desired vertebral segments, provide optimal balance in coronal and sagittal planes by correcting the curve(s) through fusing the least motion segments of the spine as possible. The first fusion of a scoliotic spine was performed by Hibbs in year 1914, who presented the idea of fusing the spine to vertebrae that end up parallel to each other after application of the turnbuckle cast (31). For a thoracic pattern curve, the pioneering authors agreed on the need to fuse all levels that make up the curve (32-34). Harrington, who introduced an instrumented fusion with his rod in 1953, suggested being on the safe side by fusing above and up to two vertebrae below the curve itself (35). Moe and Goldstein stressed the importance of vertebral rotation and advocated fusion from the superior to inferior neutrally rotated vertebrae, introducing the selective thoracic fusion concept (36-39). Some 30 years after the Harrington rod, King et al. characterized five thoracic curve types and guided on determining fusion levels for each type, but advocated carrying the fusion down to the stable vertebra (18). They also introduced a term called the “flexibility index”, used to compare the flexibility of the thoracic and lumbar curves by calculating the difference in percent of correction between the thoracic and lumbar curve on supine bending radiographs. This helped differentiate between certain curve types (18). According to Moe and King, selective thoracic fusion could achieve and keep a good balance of the spine if a proper lower instrumented vertebra was chosen.

Figure 1 Coronal balance. The C7PL is dropped from the center of the C7 vertebra in the same way it is done clinically and drawn parallel to the vertical edge of the image. The CSVL is drawn upward from the middle of S1, parallel to the vertical edge of the radiograph. In a healthy and balanced spine, these lines coincide. Offset between the C7PL and CSVL marks an imbalance in the coronal plane, easily quantified in millimeters by the formula B - A = ±X. Image courtesy of Scoliosis Research Society, from (28). C7PL, plumb line dropped from C7 vertebra; CSVL, center sacral vertical line.

Figure 2 Coronal trunk shift. Thoracic trunk shift is measured on upright PA (or AP) radiographs. First, the thoracic apical vertebra needs to be identified, and its center marked. A horizontal line is drawn through the center, and the edges of the apical ribs are marked. The midpoint between the two edge points is marked, and a perpendicular line is dropped as reference. This line is referred to as the vertical trunk reference line, and the trunk shift is measured as the linear distance in millimeters between this line and the CSVL. Shift to the right is marked as a positive and to the left of the CSVL a negative value. Image courtesy of Scoliosis Research Society, from (28). PA, posteroanterior; CSVL, center sacral vertical line.
Spontaneous correction of the unfused lumbar curve was noted that helped balance out the newly-corrected thoracic curve (40). This correction was often found to be smaller than the one seen on preoperative bending images (22,41-43). Winter et al. posit that correcting a curve beyond its flexibility is an overcorrection, which causes problems in the balance of the compensatory curves (44). The balance of the fusion mass is important for adjacent segment disease occurring over time. An additional parameter was created by Frez et al. called the rod to center sacral line distance (RCSLD), rating how centered and balanced the fusion mass is to help quantify this. It consists of measuring the distance of the Harrington rod to the CSL at the cephalad and caudal ends of the instrumentation. The authors noted a gradual correction of the RCSLD (and with it, the fusion mass) happening over time, rather than a direct instant improvement (22).

As said before, coronal spinal balance showed improvement over time after Harrington instrumentation (23). A significant change in achieving correction and balancing out scoliosis came with the ascent of the Cotrel-Dubousset instrumentation in 1983. Different kind of correction was made possible by derotating or, rather, translating a scoliotic curve for (ideally) 90° about the longitudinal spinal axis (45). This maneuver showed great strength of correction, but as the experience with this new instrumentation grew, so did the frequency of reports on postoperative trunk balance issues (20,46,47). The derotation (translational) maneuver produced torsion changes in the non-fused areas of the spine, resulting in the imbalance. It was also recognized that levels chosen for correcting and balancing out scoliosis (King 2 curve) using the Harrington rod were not suitable for the CD instrumentation (20). Arlet et al. challenged the premise of the rod de-rotation maneuver being the main culprit for balance issues after CD instrumentation and surmised that the decompensation in question is a result of a lack of symmetry between the different curves, instrumentation notwithstanding (48).

Eighteen years after King, a new system of characterizing scoliotic curves emerged, as Lenke et al. published their classification, with significantly better inter- and intrarater reliability (49). They described six types of scoliosis and introduced a “lumbar spine modifier” stemming from the relation of the center sacral vertical line (CSVL) to the lumbar apical vertebra. This is different from King’s CSL, the CSVL of Lenke ignores pelvic obliquity <2 cm (49). This classification gave almost equal value to the coronal and sagittal plane and emphasized the importance of sagittal balance by accounting for kyphosis and lordosis as key factors in determining fusion levels.

Cobb was the first to describe major and minor, as well as structural and non-structural curves and Lenke et al. built upon that by creating a reproducible way of determining curve type (4). According to Lenke et al., the major curve is one of the greatest magnitudes, and it is inherently structural, while the minor curve can be either structural or nonstructural. A curve which corrects to less than 25° on maximum effort side-bending radiographs is considered nonstructural (49). The nonstructural curves balance out the structural deformity on the scale of the entire spine; however, over time, it too can increase and become structural. Lenke classification undoubtedly came as a major improvement; however, its downside is failing to address the axial plane and rotation of the spine to provide the ultimate 3D surgical decision guide.

**Sagittal (IM) balance in AIS**

The acquisition of erect posture and consequent bipedalism represent the most important evolutionary adjustment for our species. The earliest hominid with a bipedal specialization is the Ardipithecus ramidus, dating back to 4.4 million years ago (50). However, it was not until the emergence of Homo erectus some 1.9 million years ago that hominids grew long legs and became exclusively terrestrial (51). This change not only broadened the scope of our gaze and freed our hands for greater endeavors, but also caused significant changes in our spinal column. Being upright forced our spine to assume an S-shape when viewed from the side (Figures 3,4). It is this shape that allows for even weight distribution and movement flexibility, through subsequent opposing curves. Hominids became the only species in existence with a lordosis of the lumbar spine (52). The newborn infant of the Homo sapiens has a straight spine. Cervical lordosis (CL), thoracic kyphosis (TK) and lumbar lordosis (LL) develop through upright stance and progressive ambulation. The LL, dependent on the shape of our gaze and freed our hands for greater endeavors, but also caused significant changes in our spinal column. Being upright forced our spine to assume an S-shape when viewed from the side (Figures 3,4). It is this shape that allows for even weight distribution and movement flexibility, through subsequent opposing curves. Hominids became the only species in existence with a lordosis of the lumbar spine (52).

The newborn infant of the Homo sapiens has a straight spine. Cervical lordosis (CL), thoracic kyphosis (TK) and lumbar lordosis (LL) develop through upright stance and progressive ambulation. The LL, dependent on the shape of the pelvis, influences the TK and gives it its size and shape, which again drives the shape of the CL. The incident, or a combination thereof, that spark scoliosis in some children remain unknown, but the upright sagittal spinal biomechanics undoubtedly play a paramount role (53,54).

Assessing global sagittal balance in patients with scoliosis is extremely important, especially before surgery, because it can help avoid complications of imbalance, the progression of deformity, adjacent segment disease, and pseudarthrosis.
A balanced posture is achieved when the spine and pelvis are aligned in a way that provides horizontal gaze with minimal energy output. Although a whole battery of parameters exists, evaluation of global spinal balance (both sagittal and frontal) is usually done by measuring the sagittal vertical axis (SVA) and FB on plain radiographs (55,56). In the sagittal plane, the position of the center of C7 vertebra is assessed with the femoral head axis and the posterior edge of T2. Thoracic kyphosis is measured from the upper-endplate of T2 to the lower endplate of T12 using the Cobb method. The upper thoracic spine is the most difficult to image, and it is a common occurrence not to have a clear shot of T2 on a radiograph, due to superposition of overlapping structures. Proximal thoracic kyphosis is measured from the upper-endplate of T2 to the lower endplate of T5. Mid/lower thoracic kyphosis is measured from the upper-endplate of T5 to the lower endplate of T12. Image courtesy of Scoliosis Research Society, from (28).

Thoracic sagittal alignment is measured from the upper-endplate of T2 to the lower endplate of T12 using the Cobb method. Figure 3 shows the thoracic sagittal alignment.

Thoracolumbar sagittal alignment is measured from the upper-endplate of T10 to the lower endplate of L2 using the Cobb method. Lumbar sagittal alignment is measured from the upper-endplate of T12 to the S1 endplate. The S1 endplate can sometimes be difficult to identify by a straight line, so an alternative is to draw a line perpendicular to the posterior sacral cortex and draw a perpendicular to it at the level of S1. Image courtesy of Scoliosis Research Society, from (28).

Figure 3 Thoracic sagittal alignment. Figure 4 Thoracolumbar/lumbar sagittal alignment.
of the sacral plate. The C7 was chosen as a reference point over T1 because of the visibility on lateral radiographs. The plum line dropped from C7 vertebra (C7PL) is ideally located at the posterior edge of the sacral plateau, and this position is deemed very stable, while displacement in front or behind this point shows an unstable situation (Figure 5). Measurement of C7PL excursion should be done on calibrated radiographs. The observed migration of C7PL backward from childhood to adulthood is normal, however, in scoliosis and degenerative spinal changes, it is often placed anterior to the femoral heads (57,58). Pasha et al. reported that SVA, sagittal pelvic parameters, T4-T12 kyphosis, and frontal Cobbs all exert a relevant influence on postural balance in AIS (59). Mac-Thiong et al. consider measuring global balance using linear parameters to be error-prone and suggest including the spinal-sacral angle, spinal tilt angle, and spinal-pelvic tilt angle to the evaluation to improve on the accuracy (58).

Dickson et al. reported that asymmetry in the median (mid-sagittal) plane is the essential lesion in the advent and progression of idiopathic scoliosis, using flattening or even reversing normal TK to a lordosis at the apex of deformity (60,61). The authors further claim that the increase in anterior apical vertebral height combined with distortion of the posterior end-plate suggest that AIS has a similar, only reversed pathological process to that of Scheuermann’s disease (60,62). Reduction of TK, seen mostly in thoracic scoliotic curves, has been well reported in the literature (56,60,63-67). Small TK in patients with thoracic AIS curves is related to a disturbance of vertebral body growth, which shows the greatest influence on TK comes from the shape of the vertebrae and intervertebral discs (65,68). This reduction cannot remain isolated in a closed, interdependent system such as the human spine. An interesting finding of a CL volte-face to a kyphosis with an average value of 10±18° was reported by Roussouly et al. in their series of 132 AIS patients before surgery (56). Hilibrand et al. were the first to note a significant inverse relationship between thoracic and cervical kyphosis and hypothesized the changes to be compensation to permit a horizontal line of vision (69).

The lumbar spine acts as a link between the pelvis and upper segments of the spine and is a failsafe with the ability to compensate for changes in the thoracic levels to give an overall balanced result, especially after surgical treatment for the selective fusion of isolated thoracic curves (70). The observation that the young population tolerates imbalance better than the adults stems from a LL of greater magnitude and higher mobility that they exhibit. Determining the LL limits is not always straightforward, and the method that produces most accurate measurements is by using the inflection point of Berthonnaud for the proximal limit, where TK transitions into LL (71). The LL is not strongly
influenced by spinal morphology, as opposed to TK, its’ main driver is the pelvic geometry, especially the sacral slope (SS) which is robustly affected by the value of pelvic incidence (PI) (72-77). Legaye et al. reported a value of LL equal the sum of PI plus 10°, while TK resembles PI (73). Literature shows that values for sagittal alignment of the spine are aberrant in AIS across the board, but the pelvic alignment remains ever so slightly disrupted (56,65,78,79). All the measurements stated above may be of little practical meaning, as many would argue that measuring kyphosis and lordosis on a lateral radiograph is inconsequential because it does not depict the true sagittal shape of the spine and distorts the understanding of sagittal biomechanical loading (61,67,80). However, going into too much detail using a 3D classification system based on an assessment of geometric torsion and vertebral morphometry is too complex to be used in a busy clinical setting (81).

Figure 6 Spinopelvic parameters. Sagittal pelvic parameters assessed from the standing lateral radiograph (in AIS, while in non-ambulating children with EOS the spinopelvic parameters can also be measured on sitting radiographs). Landmarks needed for measurement are the hip axis (located in the middle of the line connecting the centers of the femoral heads) and the middle of the sacral plate. Pelvic incidence is always equal to the sum of pelvic tilt and sacral slope. Image provided courtesy of Spine LWW, from (65). AIS, adolescent idiopathic scoliosis.

Beaufé, is based on the formula stating that PI equals the sum of pelvic tilt (PT) and SS (PI = PT + SS) (Figure 6) (73,82). PI is an intrinsic, anatomical parameter, constant during childhood and slowly growing until adulthood, while PT and SS are positional parameters able to change through rotation of the pelvis around the femoral heads (52,79,83). The value of PI is significantly increased in AIS patients at 57.3±13.8° when compared to values of 51±9.7°, 46.8±11.2°, and 47.4±7.5°, respectively, seen in normal adolescents (65,73,75,84). Sagittal position of the pelvis, as determined by the PI value, shows the ability of the pelvis to compensate for any imbalance. A low PI value does not allow for much retroversion of the pelvis, while the situation in a high PI setting means that a bigger PT angle is possible. The PT can be further limited by a hip extension (52). The minimal value of SS is 0°, equating to a horizontal sacral plate. A negative value of SS is not possible in upright subjects (52). As noted, before, PI determines the size of the LL—low PI values (vertical pelvis) equal a tendency for a flatter lordosis, while high PI (horizontal pelvis) is associated with marked lordosis (73).

Conclusions

As our understanding of scoliosis biomechanics progressed, and our instrumentations gave us more power and precision, a strategic shift occurred in spinal surgery. Instead of aiming for maximal correction of the scoliotic curve, we now understand attaining the best possible coronal and sagittal balance in conjunction with curve correction is paramount in AIS treatment. This review attempts to provide the reader with an overview of the landmark discussions on spinal balance in AIS. When treading through the vast literature on this topic, one can easily be overwhelmed by the inconsistencies from how a radiograph is taken to the way parameters are measured. As Bernhardt and Bridwell, who gave us the norm ranges of TK (20–50°) and LL (20–60°) in the 1980s emphasized, “for valid comparison of measurements, the levels and methods of measurement should be well defined” (85). We believe it would be beneficial for the worldwide spinal community to make a broad-reaching organized effort in promoting uniformity across the board.

Knowing and understanding the different spinal and pelvic parameters and landmarks which provide us the information on the anatomical position of the spine and pelvis is mandatory for today’s spinal surgeons. Over the years, the sagittal balance has taken the spotlight away
from the balance in the coronal plane, so it is now widely appreciated how much fine-tuning the sagittal spinal profile benefits the patients. However, in the end, the main goal of surgery when treating any spine deformity remains to be a spine that is well balanced in all 3 anatomical planes.

Many tried to help by providing cookbooks of a sort so that everyone could choose the correct fusion levels and achieve the ultimate balanced spine in AIS patients to last them a lifetime. However, so far, every system of classifying scoliotic curve fell short of the holy grail. Modern technologies in diagnostics, such as the EOS system, together with work in the field of 3D spinal morphology may provide us with the ultimate classification to improve our results in taking care of AIS patients (86-91). Valuable input is also coming from authors studying early-onset scoliosis, as Spurway et al. presented their new method of measuring the true length of a spine affected by scoliosis, so we can better rate the all-important spinal growth during treatment and follow-up (92).

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