# Aetiological process of idiopathic scoliosis: from a normal growing spine into a complex 3D spinal deformity

Tom PC Schlösser
Athanasios I Tsirikos
René M Castelein

## Abstract

In more than a century of dedicated research into its aetiopathogenesis, many attempts have been made to understand the exact cause of idiopathic scoliosis. In the literature, the number of causal theories is overwhelming and the aetiology of adolescent idiopathic scoliosis (AIS) is regarded as 'multi-factorial'. This overview focusses on recent studies that describe the changes from a normal spinal anatomy into the complex three-dimensional deformation and support the hypothesis that several paediatric deformities are a consequence of the unique way the human spine is biomechanically loaded. This has nothing to do with bipedalism, but with the way gravity and muscle tone translate to the unique sagittal shape of the spine, with its pelvic and lumbar lordosis, and the possibility to simultaneously extend the hips and knees. This leads to three rather than two forces acting continuously on the spine axial, anterior and posterior shear. An excess of anterior shear can result in spondylolisthesis and an excess of axial loading can cause osteochondrotic lesions. Unique for human are posterior shear forces, an excess of these result in decreased rotational stiffness of the involved vertebral segments. Certain sagittal spinal profiles, especially in girls around the pubertal growth spurt, predispose for development of a rotational deformity, as is idiopathic scoliosis. Once the growing spine decompensates into an idiopathic scoliosis, it will follow the right-sided rotational pattern that is already present in the non-scoliotic adolescent spine. The rotational deformation ultimately leads to rotatory lordosis around the apices of the curvatures and has major impact on lung function and quality of life.

***Tom PC Schlösser*** *MD PhD Consultant Orthopaedic Spine Surgeon, Department of Orthopaedic Surgery, University Medical Centre Utrecht, Utrecht, the Netherlands and Scottish National Spine Deformity Centre, Royal Hospital for Sick Children, Edinburgh, UK. Conflicts of interest: none declared.*

***Athanasios I Tsirikos*** *MD FRCS PhD Consultant Orthopaedic and Spine Surgeon, Scottish National Spine Deformity Centre, Royal Hospital for Sick Children, Edinburgh, UK. Conflicts of interest: none declared.*

***René M Castelein*** *MD PhD Consultant Orthopaedic Spine Surgeon, Department of Orthopaedic Surgery, University Medical Centre Utrecht, Utrecht, the Netherlands. Conflicts of interest: none declared.*

**Keywords** adolescent idiopathic; aetiology; genetics; mechanical theory; risk factors; scoliosis

## Introduction

The most common type of scoliosis is idiopathic scoliosis, which represents a three-dimensional (3D) deformity of the spine and trunk that primarily affects previously healthy children. The term 'idiopathic' (from the Greek: ἴδιος = one's own and πάθος = suffering) is not only a synonym for 'unknown', but is meant to imply that the condition arises spontaneously and there is no readily apparent physical impairment or previous medical history linked to the disorder.[1] In more than a century of dedicated research into its aetiopathogenesis, many attempts have been made to understand the exact causation of idiopathic scoliosis. The number of aetiological theories published in the literature is overwhelming and its aetiology is called 'multi-factorial'.[2] According to Rothman's concept for causality in medicine, as well as Burwell's concept for adolescent idiopathic scoliosis (AIS) specifically, this term reflects that there is not one distinct cause, but rather a concurrence of exposure to different risk-factors during the causation process of the disease that induces the development of idiopathic scoliosis (Figures 1 and 2).[3]

In the last decades, many aetiological studies focused on either neuromuscular, genetic or biomechanical risk factors, the bone metabolism and other metabolic pathways. As of yet, however, idiopathic scoliosis lacks an agreed aetiological theory, because all studies focused primarily on a single potential risk factor, effect sizes have not been determined and no studies on a potential causal chain have been performed. Furthermore, there are no longitudinal data on abnormalities in idiopathic scoliosis patients before the spine started to grow deformed.[1]

Multiple recent studies described the changes from normal anatomy into the complex 3D pathoanatomy of the spine and support that idiopathic scoliosis is a consequence of a relative (compared to the integrity of the spine's stabilizers) excess of biomechanical loading in certain areas of the spine. These studies led to the concept that intrinsic spinal biomechanics of the growing spine are a key risk factor within the aetiological cascade of idiopathic scoliosis. While the exact cellular and molecular mechanisms of disease development remain largely unknown, in order to better understand the 3D pathoanatomy of idiopathic scoliosis, this biomechanical concept will be the main focus of our comprehensive review.[4]

## Neuromuscular risk factors

Since all neuromuscular disorders that act on the growing body inevitably lead to the development of (neuromuscular) scoliosis, from the beginning it has been inferred that idiopathic scoliosis is the result of a *forme fruste* of neuromuscular disease. This hypothesis has started in the 1940s with the suggestion that a latent form of poliomyelitis would play a role. Vaccination for poliomyelitis, however, has defeated the disease, but not the occurrence of idiopathic scoliosis. Modern day imaging has led to theories that brain stem or spinal cord dysfunction, such as syringomyelia or Chiari type I malformation, may be the cause of subtle muscle imbalance and lead to idiopathic scoliosis.[5]

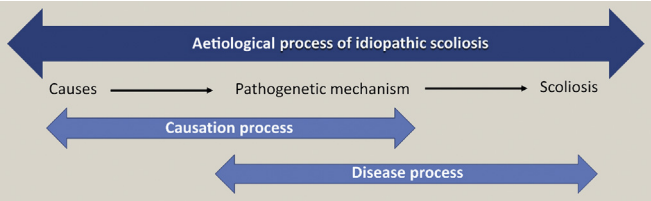


**Figure 1** A description of the different phases in the aetiological process of idiopathic scoliosis.

Nowadays, these deformities are not considered as idiopathic, but as 'scoliosis associated with intraspinal anomalies'.

Many patients with an idiopathic scoliosis function very well and are active in sports up to the moment that they reach puberty and develop a curvature of the spine. After cessation of growth they often do not manifest any other abnormality than their spinal deformity, and they certainly have no neurological disability. The drive for understanding the cause of idiopathic scoliosis has led to a large number of studies on subclinical neuromuscular functioning and abnormalities of idiopathic scoliosis patients, as well as postulation of multiple aetiological theories on different mechanisms that influence spinal balance. These include brain asymmetry, cerebellar morphometry, asymmetrical or impaired proprioception or impaired paravertebral muscle strength. Strong evidence, however, is lacking for a consistent pattern of occurrence of idiopathic scoliosis and an associated neuromuscular abnormality.[1]

## Genetic risk factors

AIS is more often (6–11%) seen in daughters of mothers with idiopathic scoliosis, and this suggests a genetic risk factor in AIS. The genetic component of AIS has also been strongly implicated by several studies on twins. As early as 1875, high concordance rates have been observed among twins. In a meta-analysis on 68 twin pairs published in 1997, concordance rates in monozygotic twins were 73% versus 36% in dizygotic twins.[6] More recent studies on Scandinavian twin registries (twin pairs with scoliosis, n = 1096 and n = 274) have demonstrated much lower pairwise concordance rates of 11–40% and 4–8% for mono- and dizygotic twins respectively.[7,8] Furthermore, they estimated that 38% of the variance in the risk of developing scoliosis is the result of genetic versus 62% of environmental risk factors.

For genetic studies in AIS, it seems problematic to identify causative AIS genes because AIS does not often follow the classic mode of Mendelian inheritance. Four genome wide association studies identified some common variants (e.g. POC5, CHD7, CHL1, LBX1, PAX1 and ADGRG6) that may be important for the aetiopathogenesis of AIS; however, most can only be traced in a sub-selection of AIS patients/families with scoliosis. Furthermore, the exact cellular and molecular mechanisms of disease development remain largely unknown for these loci. In

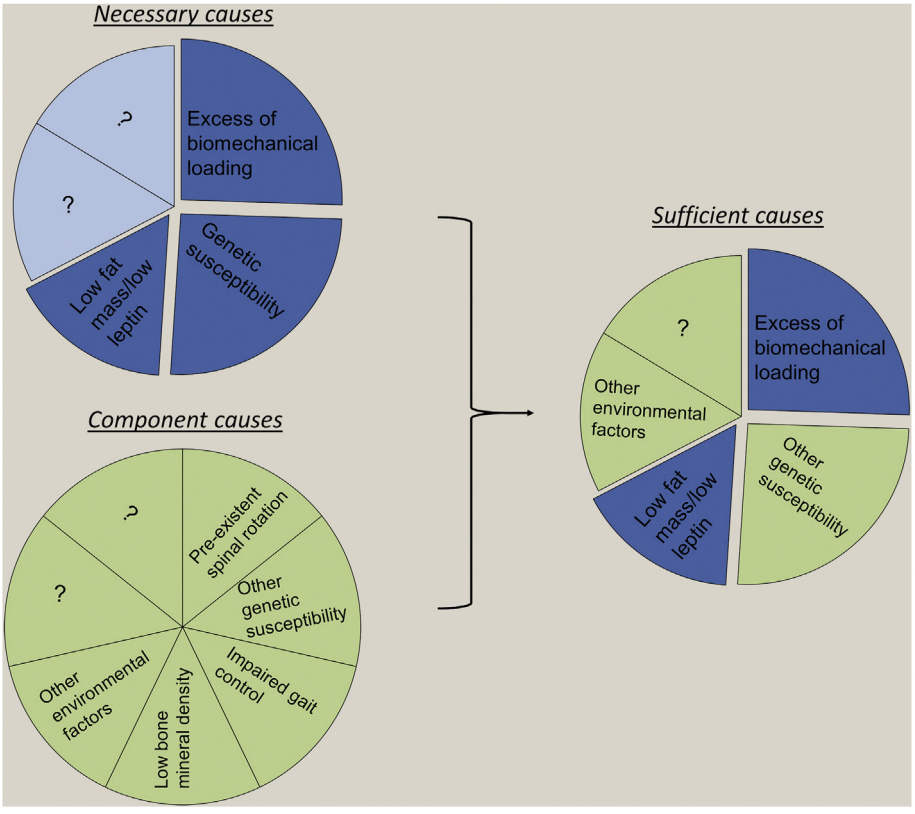


**Figure 2** According to Rothman's concept for causality in medicine, causation is defined as a concurrence of exposure to different necessary and component cause/risk-factors during the causation process of the disease that in different combination can be a sufficient cause for the development of idiopathic scoliosis. None of the causes is in itself the only necessity for starting the disease process. The effect sizes of the different causes are illustrative, but yet unknown.

summary, it can be concluded that the current data of genetic studies support a complex polygenic mode of inheritance of AIS.[9]

## Intrinsic spinal risk factors

As mentioned above, multiple recent studies described the changes from normal anatomy into the complex 3D pathoanatomy of the spine and support the key role of biomechanical loading on this uniquely shaped structure in the sagittal plane for AIS development. In order to understand the 3D pathoanatomy of idiopathic scoliosis, these well-known characteristics of the disorder will be discussed in this overview:

1. **Human spinal evolution:** Idiopathic scoliosis is related exclusively to humans and has not been observed in any other mammalian.[10] In humans, all primary curves develop in the mid-thoracic, thoracolumbar or mid-lumbar region.
2. **Epidemiology:** AIS, which is the most frequent form of idiopathic scoliosis, normally progresses around the adolescent growth spurt (80%) while girls are far more often and severely affected (sex ratios of 2.7–8.4, depending on curve severity).[11]
3. **Convexity:** Most primary thoracic curves in adolescent idiopathic scoliosis are right convex (85–90%).[11]
4. **3D pathogenesis:** Once the spine decompensates into an idiopathic scoliosis, the vertebral rotation always leads to a rotatory lordosis around the apices of the curvatures (lordoscoliotic deformity), affecting the thoracic spine and also compensatory curves of scoliosis with known aetiology, which can have significant impact on lung function and quality of life.[12,13]

### Human spinal evolution

There is no essential difference between human and all other vertebrates regarding spinal architecture. This is relatively uniform throughout all species with broad vertebral endplates and discs to withstand axial loading, as well as posteriorly located synovial joints and protuberances for muscle and ligament attachment to withstand anteriorly directed shear loads. Humans, however, have a unique combination of fully upright sagittal spino-pelvic alignment and fully upright bipedal ambulation. Due to this configuration, *Homo sapiens* is the only species that can simultaneously extend both hips and knees, putting the body's centre of gravity straight above the pelvis. In contrast, bonobos and chimpanzees, human's closest relatives, consistently ambulate with a flexion contracture of the hip and knee with their centre of gravity being in front of the pelvis. It is generally accepted by anthropologists that human habitual bipedalism can be attributed to the morphological changes of the pelvis in human evolution (development of a lordotic angulation between the ischiac and iliac bone) and the development of lumbar lordosis, a prerequisite to be able to walk fully upright (Figure 3).[14]

This sagittal spinal configuration poses unique loads on the human spine that have been shown to lead to a reduction of rotational stiffness of all segments that are posteriorly inclined in the upright position (between the apex of thoracic kyphosis and lumbar lordosis) (Figure 4).[15]

From this perspective, Janssen et al.[16] showed that posterior shear loads act on all posteriorly inclined segments of the spine as determined by each individual's sagittal profile. Therefore, the more the spine exhibits areas with posteriorly tilted vertebrae, the more these segments are prone to develop a rotational deformity, in other words idiopathic scoliosis.

### Epidemiology

It has already been known for decades that paediatric spinal deformities have a well-known age-related preference and gender-related distribution. For example, AIS develops most frequently in girls around the adolescent growth spurt, Scheuermann's kyphosis predominantly in boys around the same phase (which occurs approximately 2 years later), and infantile idiopathic scoliosis in boys around the infantile growth spurt. In 2009, Janssen et al.[16] demonstrated the variance in the segments on which posteriorly directed shear loads act in asymptomatic young adults by measurement of the posterior inclination of individual vertebrae on standardized, low dose biplanar radiographs of the spine. It was observed that individual vertebrae in different spinal regions are more posteriorly inclined in females than in males and that the posteriorly inclined segments of the non-scoliotic spines correspond to the rotated segments in AIS. In order to understand the typical timing of the onset of idiopathic

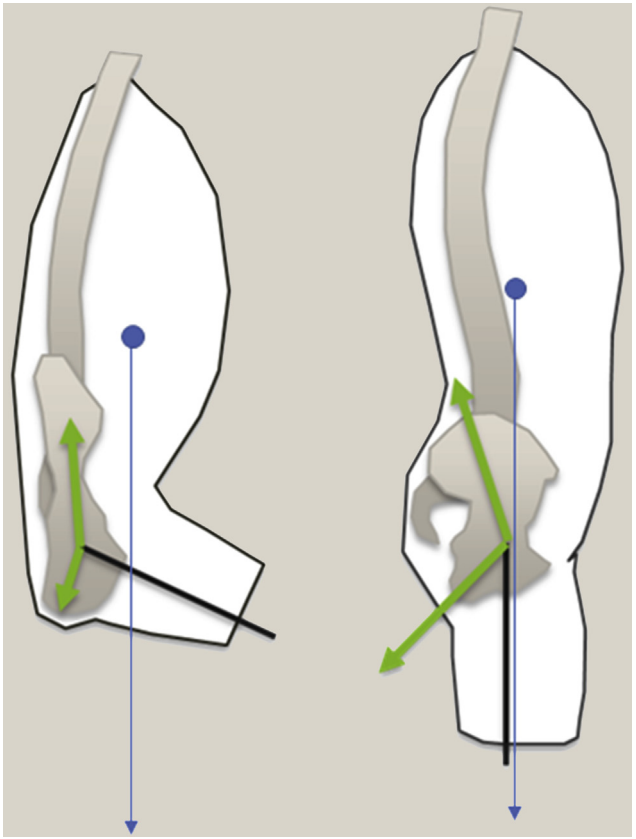

**Figure 3** In the course of human evolution, the development of lordosis between the ischium and ilium allowed for ambulation in a fully upright position, with the body's centre of gravity directly above the pelvis, maintaining full extension of the hips and knees. It is important to realize that this posture is essentially different from all other vertebrates, including primates. This 'pelvic lordosis' led to the double-S-shape configuration of the spino-pelvic complex, and unique biomechanical forces.

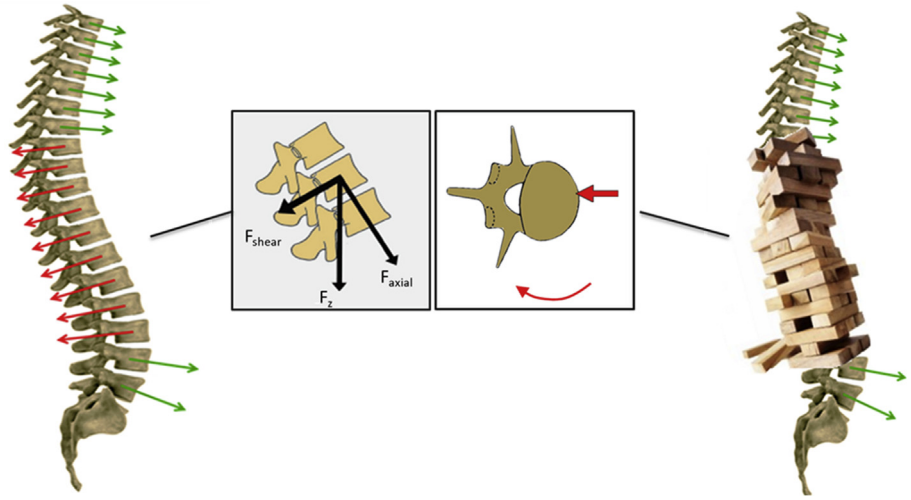


**Figure 4** All posteriorly inclined segments of the spine, as determined by each individual's sagittal profile are affected by posteriorly directed shear loads (red arrows). In an experimental set-up, Kouwenhoven et al.[15] have shown that an excess of posterior shear loads results in diminished rotational stiffness of spinal segments.

scoliosis at the adolescent age and in girls, the development of the sagittal spinal profile during the normal phases of the adolescent growth spurt was investigated by Schlösser et al.[17] in 156 adolescents without scoliosis. The results showed that thoracic kyphosis, pelvic tilt and pelvic incidence increase during growth and that before and at the peak of the growth spurt, a greater number of vertebrae are more posteriorly inclined as compared to after the growth spurt. Moreover, the spines of girls at the peak of the growth spurt showed more posterior inclination and a smaller thoracic kyphosis as compared to boys (Figure 5). Of course, this can only be visualized in a rather simplified manner, it is not only gravity but certainly to a large extent also the continuous muscle tone that acts on the different areas of this curved structure.

This implies that in girls around their peak growth velocity the spine is subject to greater posteriorly directed shear loads, and thus shows less resistance to rotation. This can explain why AIS – under still undetermined circumstances during growth – occurs more in girls than in boys and the incidence of Scheuermann's kyphosis is greater in adolescent boys.

According to this concept, it can be inferred that the area of the spine in which a rotational deformity has a chance to develop, is based on differences in sagittal spino-pelvic alignment before the onset of the deformity. Systematic analysis of the sagittal profile of thoracic versus thoraco-lumbar/lumbar scoliosis at the earliest phase of the disease (mild curves of 10–20°) revealed that already at this very early stage, thoracic kyphosis and posterior inclination of thoracic AIS differs significantly from thoraco-lumbar/lumbar AIS, as well as from controls. More precisely, in thoracic scoliosis most thoracic vertebrae were more backwardly inclined as compared to thoraco-lumbar/lumbar scoliosis and vice versa.[18]

## Curve convexity

In addition to the concept of certain sagittal configurations that facilitate rotation of the thoracic and lumbar vertebrae, it can be hypothesized that once rotation occurs, it logically follows an already built-in rotation, that is pre-existent in the spine. In multiple studies, Kouwenhoven et al., Janssen et al. and Schlösser et al.,[19–21] the existence of subtle rotational patterns of the normal, non-scoliotic spine has been demonstrated both in humans and quadrupeds. The axial rotation of the main thoracic vertebrae, although smaller in magnitude, corresponds to the direction of rotation observed in infantile and adolescent

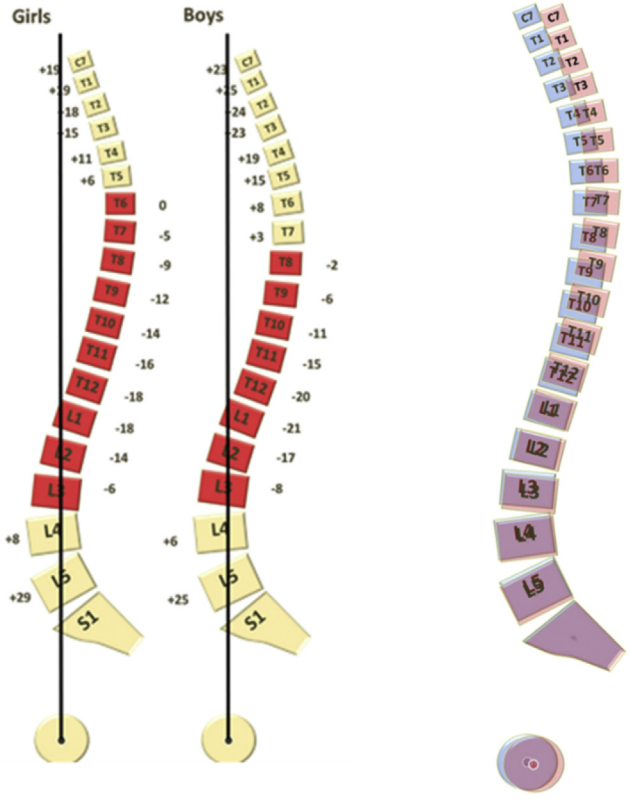


**Figure 5** Comparison of sagittal spinopelvic alignment of boys and girls at the peak of the adolescent growth shows that girls develop a relatively straighter spine through their adolescent growth spurt.[17]

idiopathic scoliosis. At the infantile age, normally the spine is slightly rotated to the left whereas at the adolescent age it is significantly rotated to the right side. In addition, the pre-existent rotational pattern of the human spine has been related to organ anatomy and body position but not to handedness.[20] Recently, these hypotheses were confirmed in a study on a unique set of 16 patients with scoliosis and *situs inversus*; Schlösser et al.[22] demonstrated a 94% match between organ orientation and curve convexity.

### 3D pathogenesis

The Scoliosis Research Society defines scoliosis as a lateral curvature of the spine of more than 10° in the coronal plane. This formal definition underestimates the fact that it is actually a complex 3D spinal deformity. Already in the late 19th and early 20th century, using cadaver specimens, anatomists carefully described that AIS involves changes in the coronal, transverse, as well as the sagittal plane.[23,24] In the coronal plane, the deformity is characterized by lateral deviation and lateral bending, in the transverse plane by axial rotation, asymmetrical growth of the pedicles and asymmetrical closure of the neurocentral cartilages and in the sagittal plane by lordosis of the apical segments and hypertrophy of the facet joints. A typical feature of the curves in AIS is the coupling between the phenomena in the three different planes. In 1952, Somerville[25] and Roaf[26] described that during the development of AIS the vertebral bodies rotate away from the midline towards the convexity, to a more lateral position than the posterior elements of the spine. By definition, axial rotation towards the convexity of the curve leads to a spinal column that is laterally flexed and is elongated anteriorly than posteriorly, in other words a rotatory lordosis develops across the scoliotic apex. As a consequence of the development of this regional rotatory apical lordosis in AIS, Dickson et al.[27] reported among 70 AIS patients that instead of the normal thoracic kyphosis, 75% of patients presented with thoracic lordosis, 24% with a straight thoracic spine and in only 1% thoracic kyphosis existed.

Although the 3D aspect of AIS has been studied for over a century, only recently innovative 3D imaging methods (biplanar radiography and 3D CT reconstructions) provided the opportunity to investigate the true 3D morphology and especially the sagittal deformation of the different areas and structures of the scoliotic spine.[12,13] Interestingly, quantitative description of the 3D morphology of AIS revealed that: (1) the 3D development of AIS curves follows a rather uniform pattern with coupling of the different aspects of the deformity in all three planes and (2) the apical levels of all AIS curves, primary as well as compensatory, thoracic as well as thoraco-lumbar/lumbar is characterized by greater anterior length (Figure 6).

Furthermore, the individual contributions of the discs and vertebral bodies to the true 3D deformity of the spine in AIS were analyzed. In contrast to previous 2D studies, Schlösser et al.[28] found that in scoliosis the intervertebral discs were at least three times more deformed in the coronal, true transverse and true sagittal plane than the vertebral bodies. Anterior-posterior and coronal wedging was more pronounced at the apices of the curves, whereas mechanical torsion was found in all regions of the spine. Based on these results it can be concluded that the excess of anterior length is not a global but rather a regional phenomenon; also that, since the deformity originates much more in the disc than in the bone and has been observed in scoliosis with known aetiology, it seems more of a passive phenomenon than an active growth process. The rotational deformation ultimately leads to rotatory lordosis around the apices of the curvatures, flattening of the normal thoracic kyphosis and has significant impact on lung function and quality of life.[29] Also in the compensatory curves of scoliosis with known aetiology, this 3D phenomenon can be observed.

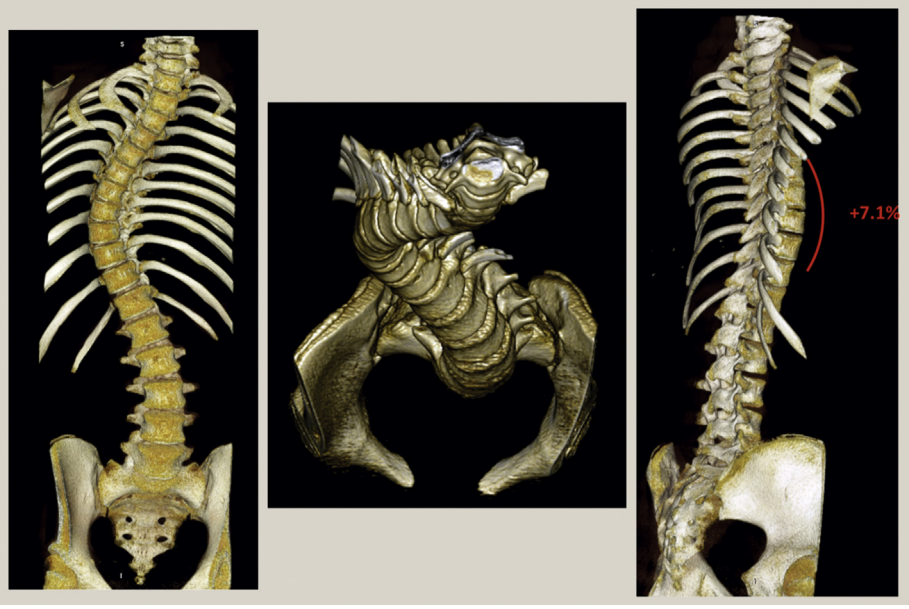


**Figure 6** A frontal, cranial and true lateral view of CT reconstructions of the complex three-dimensional deformation of the spine in idiopathic scoliosis is shown. In the coronal plane the deformity is characterized by lateral deviation and lateral bending, in the transverse plane by axial rotation and in the sagittal plane by lordosis of the apical segments.

## Conclusions

Multiple studies support the hypothesis that AIS is the result of decreased rotational stiffness of the spine due to an excess of posteriorly directed shear loads, related to man's unique sagittal profile. These studies also demonstrated that once the spine decompensates into an idiopathic scoliosis it will follow the pre-existent rotational pattern of the non-scoliotic spine. This spinal deformation ultimately leads to rotatory lordosis around the apices of the curvatures and has considerable impact on quality of life. We can conclude that AIS has an intrinsic biomechanical basis: An imbalance between the biomechanical loading of the upright human spine (i.e. posteriorly directed shear loading) on the one hand and the body's compensating mechanisms on the other.[4]

For further clarification of the aetiology of AIS and the role of posteriorly directed shear forces, there is a need for a large-scale investigation in which children at risk for scoliosis should be longitudinally followed during their adolescent growth spurt, starting before the onset of the deformity. Preferably, multiple potential aetiological risk factors should be included to reveal the aetiological cascade of idiopathic scoliosis.[3] Modern radiation-free techniques such as 3D spinal ultrasound or MRI may help to withdraw the ethical concerns in the case of a longitudinal study of spinal morphology in asymptomatic children.

As research continues on the pathogenesis of AIS, it can be expected that the biological and mechanical mechanisms in the pathogenesis of AIS can be revealed and possible risk factors for the development and progression of the deformity can be identified at an early stage, when less invasive treatment is still an opportunity. This is needed in order to develop adequate causal treatment, as until now, the treatment of AIS is focussed on the end result of the disease process. ◆

## REFERENCES


1 Schlosser TP, van der Heijden GJ, Versteeg AL, Castelein RM. How 'idiopathic' is adolescent idiopathic scoliosis? A systematic review on associated abnormalities. *PloS One* 2014; **9**: e97461.

2 Kouwenhoven JW, Castelein RM. The pathogenesis of adolescent idiopathic scoliosis: review of the literature. *Spine* 2008; **33:** 2898–908.

3 Burwell RG, Clark EM, Dangerfield PH, Moulton A. Adolescent idiopathic scoliosis (AIS): a multifactorial cascade concept for pathogenesis and embryonic origin. *Scoliosis Spinal Disord* 2016; **11**. 8-016-0063-1. eCollection 2016.

4 Castelein RM, van Dieën JH, Smit TH. The role of dorsal shear forces in the pathogenesis of adolescent idiopathic scoliosis–a hypothesis. *Med Hypotheses* 2005; **65:** 501–8.

5 Gupta R, Sharma R, Vashisht S, et al. Magnetic resonance evaluation of idiopathic scoliosis: a prospective study. *Australas Radiol* 1999; **43:** 461–5.

6 Kesling KL, Reinker KA. Scoliosis in twins. A meta-analysis of the literature and report of six cases. *Spine (Phila Pa 1976)* 1997; **22:** 2009–14. discussion 2015.

7 Grauers A, Rahman I, Gerdhem P. Heritability of scoliosis. *Eur Spine J* 2012; **21:** 1069–74.

8 Simony A, Carreon LY, H Jmark K, Kyvik KO, Andersen MO. Concordance rates of adolescent idiopathic scoliosis in a Danish twin population. *Spine (Phila Pa 1976)* 2016; **41:** 1503–7.

9 Cheng JC, Castelein RM, Chu WC, et al. Adolescent idiopathic scoliosis. *Nat Rev Dis Primers* 2015; **1:** 15030.

10 Janssen MM, de Wilde RF, Kouwenhoven JW, Castelein RM. Experimental animal models in scoliosis research: a review of the literature. *Spine J* 2011; **11:** 347–58.

11 Weinstein SL, Dolan LA, Cheng JC, Danielsson A, Morcuende JA. Adolescent idiopathic scoliosis. *Lancet* 2008; **371:** 1527–37.

12 Newton PO, Fujimori T, Doan J, Reighard FG, Bastrom TP, Misaghi A. Defining the "Three-Dimensional sagittal plane" in thoracic adolescent idiopathic scoliosis. *J Bone Joint Surg Am* 2015; **97:** 1694–701.

13 Schlosser TP, van Stralen M, Chu WC, et al. Anterior overgrowth in primary curves, compensatory curves and junctional segments in adolescent idiopathic scoliosis. *PloS One* 2016; **11**: e0160267.

14 Schlosser TP, Janssen MM, Hogervorst T, et al. The odyssey of sagittal pelvic morphology during human evolution: a perspective on different Hominoidae. *Spine J* 2017; **17:** 1202–6.

15 Kouwenhoven JW, Smit TH, van der Veen AJ, Kingma I, van Dieën JH, Castelein RM. Effects of dorsal versus ventral shear loads on the rotational stability of the thoracic spine: a biomechanical porcine and human cadaveric study. *Spine* 2007; **32:** 2545–50.

16 Janssen MM, Drevelle X, Humbert L, Skalli W, Castelein RM. Differences in male and female spino-pelvic alignment in asymptomatic young adults: a three-dimensional analysis using upright low-dose digital biplanar X-rays. *Spine (Phila Pa 1976)* 2009; **34:** E826–32.

17 Schlosser TP, Vincken KL, Rogers K, Castelein RM, Shah SA. Natural sagittal spino-pelvic alignment in boys and girls before, at and after the adolescent growth spurt. *Eur Spine J* 2015; **24:** 1158–67.

18 Schlosser TP, Shah SA, Reichard SJ, Rogers K, Vincken KL, Castelein RM. Differences in early sagittal plane alignment between thoracic and lumbar adolescent idiopathic scoliosis. *Spine J* 2014; **2:** 282–90.

19 Kouwenhoven JW, Vincken KL, Bartels LW, Meij BP, Oner FC, Castelein RM. Analysis of preexistent vertebral rotation in the normal quadruped spine. *Spine (Phila Pa 1976)* 2006; **31:** E754–8.

20 Janssen MM, Kouwenhoven JW, Schlosser TP, et al. Analysis of preexistent vertebral rotation in the normal infantile, juvenile, and adolescent spine. *Spine (Phila Pa 1976)* 2011; **36:** E486–91.

21 Schlosser TP, Vincken KL, Attrach H, et al. Quantitative analysis of the closure pattern of the neurocentral junction as related to preexistent rotation in the normal immature spine. *Spine J* 2013; **13:** 756–63.

22 Schlosser TP, Semple T, Carr SB, et al. Scoliosis convexity and organ anatomy are related. *Eur Spine J* 2017; **26:** 1595–9.

23 Nicoladoni C. Anatomie und Mechanismus der Skoliose. In: Kocher, König, von Mikulicz, eds. Bibliotheca medica. Stuttgart: Verlag von Erwin Nagele, 1904.

24 Hermann Meyer G. Die mechanik der Skoliose. *Arch für Pathol Anat Physiol für Klin Med* 1866; **35:** 225–53.

25 Somerville EW. Rotational lordosis; the development of single curve. *J Bone Joint Surg Br* 1952; **34-B:** 421–7.

26 Roaf R. The basic anatomy of scoliosis. *J Bone Joint Surg Br* 1966; **48:** 786–92.

**27** Dickson RA, Lawton JO, Archer IA, Butt WP. The pathogenesis of idiopathic scoliosis. Biplanar spinal asymmetry. *J Bone Joint Surg Br* 1984; **66:** 8–15.

**28** Schlösser TP, van Stralen M, Brink RC, et al. Three-dimensional characterization of torsion and asymmetry of the intervertebral discs versus vertebral bodies in adolescent idiopathic scoliosis. *Spine (Phila Pa 1976)* 2014; **39:** E1159–66.

**29** Jagger F, Tsirikos AI, Blacklock S, Urquhart DS. Adaptation to reduced lung function in children and young people with spinal deformity. *J Clin Orthop Trauma* 2020; **11:** 191–5.