HIRURGIA POZVONOCHNIKA 2016;13(3):108–113

SELECTED LECTURES

ON SPINE SURGERY

3D ANALYSIS OF SCOLIOTIC DEFORMITY DEVELOPMENT AND 3D CHAIN OF BALANCE IN A SCOLIOSIS PATIENT

J. Dubousset
National Academy of Medicine, Paris, France
Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, Novosibirsk, Russia

The lecture presents the views on the process of mechanical origin of scoliotic deformity of the spine and on a contribution of extraspinal departments of the locomotor system to this process.
Key Words: scoliosis, 3D deformity of the spine, 3D balance of a human trunk.

Please cite this paper as: *Dubousset J. 3D analysis of scoliotic deformity development and 3D chain of balance in a scoliosis patient. Hir. Pozvonoc. 2016;13(3):108–113. In Russian.*
DOI: http://dx.doi.org/10.14531/ss2016.3.108-113.

Any spinal deformity is characterized by two features of its three-dimensional development and mobility:

1) at the level of the spine as a whole – movement and displacement of one vertebra relative to another, i.e., pathological anatomy of the deformity and its progression;

2) at the level of a single vertebral body in 3D space – as a result of a spinal deformity impact on the organization and mobility of the vertebral body.

3D analysis of the scoliotic deformity

Torsion. Examination of various scoliotic spine specimens makes it evident that the basic three-dimensional torsional deformity becomes more understandable when evaluated simultaneously in the anteroposterior, lateral, and axial (from the top or bottom of the spinal column) projections. Comparison with the specimen radiographs clearly demonstrates that X-rays provide just a shadow (single-plane projection) of the three-dimensional reality. The so-called Cobb angle shows only the spine collapse, and nothing more. In 1976, we together with Henry Graf and Jerome Hecquet created the first schematic computerized 3D reconstruction of the scoliotic spine using two orthogonal X-ray projections. Starting with the same vertebral reference points, we developed first a linear model, then a simple planar model, and, finally, a three-dimensional model of each vertebra with reconstruction in the frontal, sagittal, and horizontal planes. These images closely reproduced specimens, which we held in hands, due primarily to clear visualization of the torsion.

As many authors (Shaw, Adams, Sommerville, Roaf, and, later, Pierre Stagnara) have already described, the deformity is actually a torsional-axial rotation. A spinal deformity cannot exist in only a single plane: each vertebra and each molecule of the bone and soft tissues are twisted. This explains a countless number of planes and axes present in the scoliotic deformity (Fig. 1). For biomechanical engineers, this means the formation of helical axes. This has been most evident in an analysis of infantile scoliotic deformities (the onset and development at age of less than 3 years) that are clinically heterogeneous because they can have a benign course and spontaneously disappear or rapidly progress, up to the most severe forms (a malignant group according to Min Mehta).

The axial projection of the created reconstruction was very impressive and made it possible to classify deformities in terms of the anatomy and progression prognosis, with three types being distinguished: 1) deformities that spontaneously and rapidly resolve to the normal state; 2) benign progressive (the Min Mehta's term) deformities reaching a Cobb angle of 70° with a severe progressive apical torsion in the axial projection, which can be derotated and completely eliminated by appropriate treatment, but, if untreated, progress to severe forms; 3) malignant progressive scoliosis (the Min Mehta's term) with a severe apical torsion involving a small number of vertebrae, which forms, by the end of the growth period, extremely severe deformities not amenable to conservative treatment and not tolerant to surgical correction (Fig. 2). I presented this study at the SRS meeting in Chicago in 1980, but did not strike a chord with colleagues. Only an engineer Shultz found it necessary to come to me and discuss the issue.

Torsion and countertorsion. A case of a single curve. At the intervertebral disc level, progression of torsion is accompanied by increased expulsion of the nucleus pulposus towards the convexity of the deformity and increased wedging of the

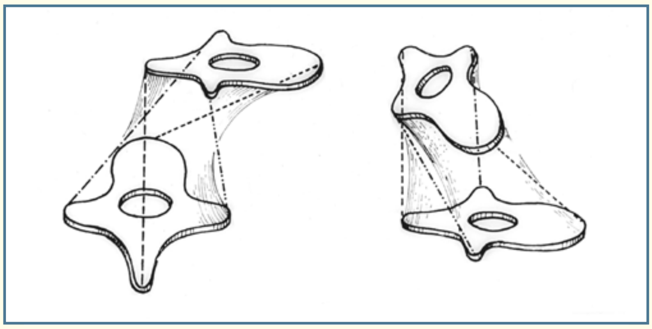

Fig. 1
Torsional-axial rotation in scoliosis: an infinite number of planes and axes

adjacent vertebral bodies, which is characteristic of structural scoliosis (Fig. 3). This may explain the fact that the nucleus pulposus acts as a lock in scoliosis correction because the nucleus, during development of a bone deformation, can not be displaced towards the concavity of the deformity due to the lack of space required for this, and the apical zone of the curve becomes rigid. That is why anterior intervention (release) that includes excision of the fibrous ring and resection the nucleus provides necessary mobility for scoliosis correction.

One of the ways to understand the torsion mechanism is to explain how the crankshaft phenomenon develops. Posterior fusion for scoliosis in a patient with incomplete skeletal growth forms a lock for a group of deformed and rotated vertebra, blocking local growth of their posterior parts in the surgical site. If the spine is straight, and posterior fusion is symmetric, continued growth of the anterior parts of the spine will result in the formation of pure lordosis. But in scoliosis, the vertebrae are already rotated, and continued anterior growth increases torsion, and posterior block acts a rotation point, around which the spine rotates like a vehicle crankshaft. This is most obvious when the spine is viewed along its vertical axis, demonstrating changes in the horizontal plane,

In the entire deformed spine, the spatial orientation of successive curves forms a torsion-countertorsion sequence. This is clearly seen in the case of spontaneous evolution or progression of the scoliotic deformity and sequential formation of the thoracic and then lumbar curve, and sometimes the lumbosacral or pelvic curve, with each of them developing in accordance with the 3D balance principles one curve develops in one direction (to the right), and the next one develops in the opposite direction (to the left) to achieve the so-called equilibrium. Of course, this occurs in the three spatial planes. A typical case of this torsion-countertorsion sequence is rotational dislocation of the spine with kyphosis located between two lordoscoliotic segments of the spine. This transition phenomenon can occur at any spinal level.

3D scoliosis imaging

A classical three-dimensional imaging technique is CT. It is based on multiple X-ray sections and is quite acceptable for a local study of the spinal column. The technique is not suitable for examination of the entire spine, especially in children, due to massive radiation exposure potentially harmful to health.

In this regard, we developed computerized 3D reconstruction for the entire spine, including the pelvis, based on two orthogonal calibrated radiographs obtained in standard projections, with the patient in the standing position (first experiments by H. Graf and G. Hecquet were performed as early as in the 1970s). This X-ray stereography provided excellent high-precision results, demonstrating the basic scoliotic deformity (translation-rotation) with a helical axis. Since 2000, we have used the so-called low-dose EOS device that is easy to operate and provides accurate 3D reconstruction of the entire skeleton in the standing position. The device was developed by a group of engineers and physicists led by a Nobel Laureate, Georges Charpak, specialists in biomechanics from the Ecole Nationale Superieure d'Arts et Metiers (ENSAM), and clinicians from the St. Vincent de Paul Hospital, Paris. The device produces highly accurate and informative images, while the radiation exposure is 860-fold lower than that of routine CT. Orthogonal plane images of the spine provide a lot of information, but a three-dimensional axial reconstruction is unique and provides a much greater amount of data on the shape and position of the spine column, using the gravity axis as a reference point. The method is very useful for studying spinal deformities in children, adolescents, and the elderly with typical age-related skeletal changes.

The effect of spinal deformity on body mobility

The normal spine has the normal shape in all planes. Spinal segments are connected at a three-dimensional equilibrium position and move around the gravity axis that, in turn, is orthogonal to the polygon support. Therefore, in this situation, we can rely on frontal, sagittal, and horizontal balances. In 1975, we introduced the concept of "cone of economy" for the body in a standing posture, based on the "chain of balance" concept that starts from the support polygon, then the lower limb skeleton and pelvis (which I called the *pelvic vertebra* in 1972), then all the spinal elements, and finally the head (*cephalic vertebra*). As the range of movements around the gravity axis over the polygon support increases, a small cone of their spatial boundaries turns into a big one. When the patient's trunk balance occurs within the small cone, the muscle supporting force is minimal (in this case, economy means a reduced muscle force). As the cone radius increases, muscle power consumption grows.

The chain of balance is needed in the norm and pathology, in standing and sitting, and in statics and dynamics. It is necessary to emphasize the strategic role of the *pelvic vertebra* (Fig. 4) in this chain, especially in the development of compensatory reactions in skeletal pathology above (spine)

Fig. 2
Age-related classification of infantile scoliosis from the best to the worst:
a – spontaneous healing;
b – benign progression;
c – malignant progression;
d – three-dimensionality of the spine in the axial projection

or below (lower limbs) the pelvis. It should also be remembered that one of the goals of the ideal balance is to maintain the horizontal gaze.

Cephalic vertebra concept. The weight of an adult head ranges from 4.5 to 5.5 kg. Its three symmetry planes (frontal, sagittal, horizontal) are connected at a point on the midline in the third ventricle roof region (pineal gland level). We claim that the perfect static balance is achieved when this point is located on the gravity line dropped from the center of the polygon support. This is fully consistent with the position of the head gravity center behind and slightly above the sella (J.M. Vital, 1986). Maybe, it acts like a neural gyroscope?

The perfect balance is strictly individual and is the result of adaptation and compensation. The concept of dynamic balance is closely related to the cone of economy concept. A dynamic measurement of pressure on the polygon support enables evaluation of changes in the cone of economy status over time. Temporal changes, e.g. aging, are accompanied by loss of muscle strength and degradation of the neural status (speed of nervous transmission and a subsequent reaction). Therefore, a balanced human body eventually becomes unbalanced over time; then, the critical level may be achieved when gross imbalance develops spontaneously, which requires a lot of effort to recover the balance, at least partially; finally, the situation of at least partial balance recovery becomes impossible. These processes can be shown on a diagram as a progression curve or, on the contrary, a recovery curve. These data may be useful for making a decision about the time of deformed spine surgical correction. An analysis of trunk movements was described by R. Ducroquet more than half a century ago (1965). An examinee was in a room completely covered with mirrors for simultaneous observation of movements in three dimensions. Under these conditions, the pelvic step that is a constant movement of the *pelvic vertebra*, giving harmony to walking, especially in the horizontal plane (Fig. 5), was described and defined. During 3D analysis of the pelvic orientation in idiopathic scoliosis, the lumbar spine torsion often extends to the pelvis level and manifests as changes in the shape of the iliac bone projection and sciatic notch or as asymmetry of the obturator foramina. Currently, optoelectronic systems (e.g., a Vicon system) using external markers make it possible to gain highly reliable data about any spatial movements and, therefore, to study the dynamic balance noninvasively. These processes are well studied in the frontal and sagittal planes, but much less in the horizontal plane. Highly informative diagrams obtained with these systems enable us to measure the involvement and nature of any displacements of anatomical structures in statics and dynamics, e.g., a role of the pelvic vertebra in compensation of any impairments of spine mobility. A perfect example is a study of the results of thoracic fusion (not below than the L2 vertebra) in 30 patients with idiopathic scoliosis. The pelvic vertebra was proven to play a great role in compensatory pro-

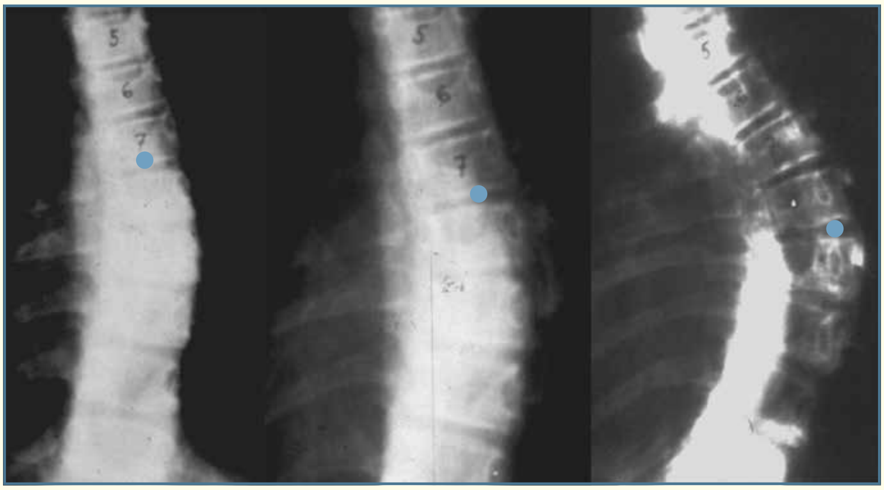

Fig. 3
Structuralization of the intervertebral discs: progressive expulsion of the nucleus pulposus towards the convexity of the curve and progressive wedging of the vertebral bodies

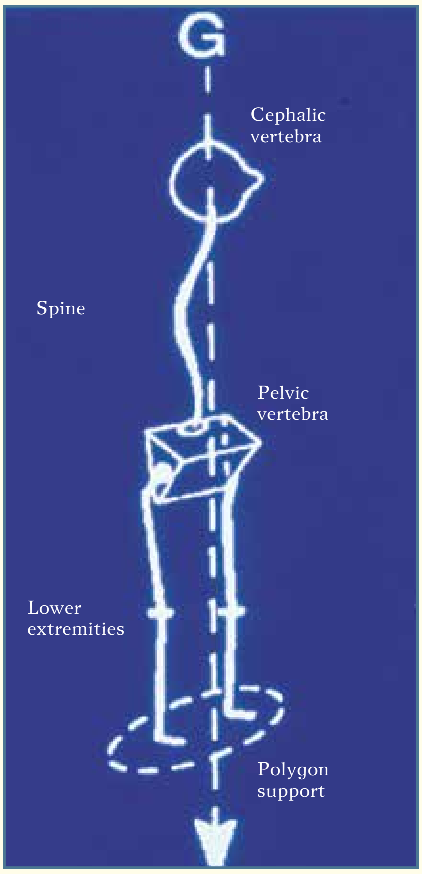

Fig. 4
The concept of the pelvic vertebra as an intercalary bone: the pelvic vertebra located in the middle is the strategic level of the chain

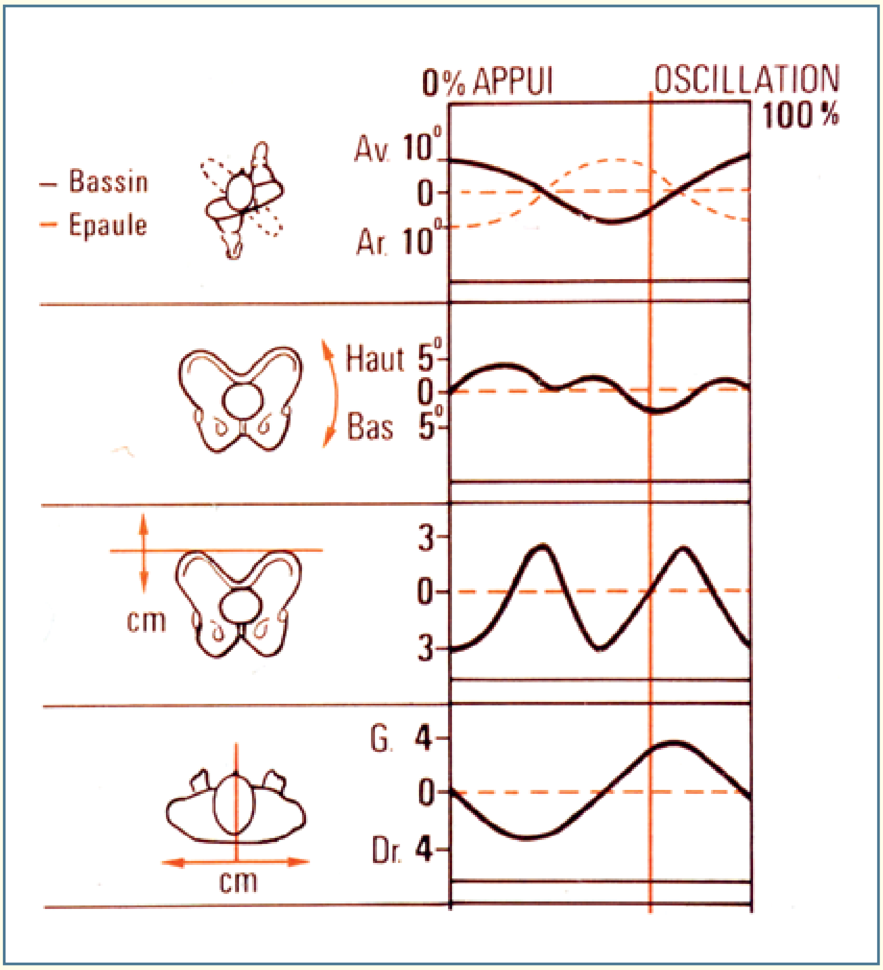

Fig. 5
Pelvic step phases

cesses, both in statics and in dynamics, 9, 18, and 30 months after surgery. In addition, all patients were examined before and after surgery using the EOS device and 3D reconstruction of the skeleton of the spine and pelvis, and we were able to demonstrate that even the *pelvic incidence* changed in 50 % of cases due to rotation within the sacroiliac joints.

Therefore, we conclude that the chain of balance for the erect trunk posture (standing or sitting) involves permanent static and dynamic adaptation of all bones and joints, from the polygon support to the *cephalic vertebra*, through the spine and *pelvic vertebra*, including, if necessary, structural changes in the bones and joints (as it may occur in the pelvic region) to achieve the horizontal gaze.

Conclusions

1. The *pelvic vertebra* plays an important role in the articular chain of the body balance (both in sitting and in standing) due to its strategic position between the spine and lower limbs in normal and pathological situations.
2. The *pelvic incidence* is an indicator of the pelvis ability to regulate the magnitude of lordosis/kyphosis to achieve a balance.
3. The pelvis function, both in statics and in dynamics, is to compensate pathological changes situated above and below the pelvis to achieve the 3D balance.
4. When the potential of postural compensation is exhausted, the pelvis can be anatomically modified (including the *pelvic incidence* in the sagittal plane) to eliminate or correct pathological conditions.

Address correspondence to:
Dubousset Jean
23 bis rue des Cordelieres, Paris, 75013, France,
jean.dubousset@wanadoo.fr

Received 11.05.2016

Jean Dubousset, Professor of Pediatric Orthopaedics, Member of the French National Academy of Medicine, Paris, France, academic adviser in the Novosibirsk Research Institute of Traumatology and Orthopaedics n.a. Ya.L. Tsivyan, Novosibirsk, Russia.