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# SELECTED LECTURES

## ON SPINE SURGERY

# THE SPINE IS THREE-DIMENSIONAL ENTITY, THOUGH 3D ALIGNMENT AND 3D BALANCE SHOULD NOT BE CONFUSED

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

The lecture represents Prof. J. Dubousset's understanding of such fundamental problems of the modern spine medicine as the balance of the body in three-dimensional space, stability and alignment of the spinal column, and describes the methods of qualitative and quantitative assessment of these parameters. Attention is also paid to the prevention of junctional kyphosis and its justification from the author's position.
**Key Words:** 3D body balance, spine in 3-dimensional space, Proximal Junctional Kyphosis.

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The difference is obvious for physiologists and choreographers but not always for surgeons. However, when we talk about a person in an upright position, we must admit that alignment is static, while balance is dynamic and associated with movement: spontaneous or automatic (Fig. 1). Radiographs on the slides presented at scientific meetings reflect only alignment (with or without success) even if the speaker does not always use the term "balance" correctly!

Interest in spine 3D reconstruction was one of the reasons that prompted me to turn to Georges Charpac and engineers of the Laboratory of Biomechanics at the Ecole Nationale Sup rieure d'Arts et M tiers (ENSAM) with a request for the development of EOS imaging system for the study of 3D-alignment of the human body from head to toes (another reason was obtaining a 3D reconstruction in order to study spine deformity in the horizontal plane). This apparatus in conjunction with low-dose spine radiography in two standard projections, the data of which are processed on the computer, provides a reliable 3D reconstruction of the whole spine (Fig. 2). Moreover, the radiation dose is 860 times less than that for CT. Three-dimensional spine imaging is possible not only in conventional (anteroposterior, lateral) projections but also axial (downward) projection exhibiting vertebral torsion included in the scoliotic arch. The possibility of examining spinal deformity in horizontal plane relative to the body gravity line has been emerging. Each vertebra can be examined separately, while the whole arch can be examined from end-to-end vertebra as well as the patient's whole body. Such 3D examination during pre- and postoperative periods is much more accurate and informative than conventional radiographs.

Quantitative evaluation of changes in the horizontal plane became possible thanks to the work by Tamas Illes and engineer Szabolcs Somoskeoy from Pecs (Hungary) published in 2009. They proposed a spinal vector for each vertebra, which allows achieving high accuracy of measurements. Comparison of 3D surface reconstruction and vertebral vectors for the same arch prior to and after treatment is highly demonstrative (Fig. 3). In case of progressive deformity, it is absolutely obvious that lateral displacement is more pronounced than progression of axial rotation. Examination of the group of 301 patients with type I scoliosis by Lenke using spinal vector showed that there are three subgroups that can be selected for the horizontal plane. That is why I advised my friend Lawrence Lenke to introduce a horizontal modifier in addition to sagittal and lumbar ones.

Carl-Eric Aubin from Montreal and 3D research group SRS made a simultaneous attempt to develop a 3D classification of idiopathic scoliosis. They used the plane of maximum deformity of each segment, which, to my mind, is controversial because a scoliotic arch cannot be placed in a single plane. Yet the attempt is useful, since it prompts the surgeon and other professionals dealing with scoliosis to the idea of horizontal plane.

In addition, the projection by Da Vinci, which presents the view of the spinal column from the top, allows quantitative evaluation of the changes. We have already described this picture in 1978 when together with Henry Graf and Jerome Hecquet created the first computer reconstruction for infantile scoliosis, which helped explaining the development of crankshaft phenomen.

Three-dimensional reconstructions obtained using EOS also allow prognosis of deformity progression at the first

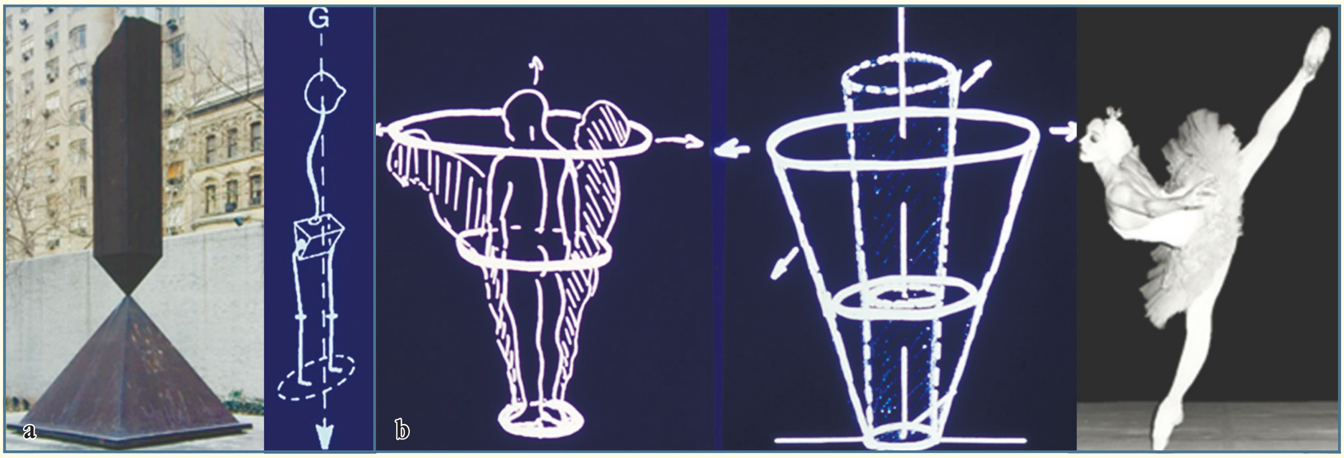


**Fig. 1**
Upright human position can be static **(a)** and dynamic **(b)**

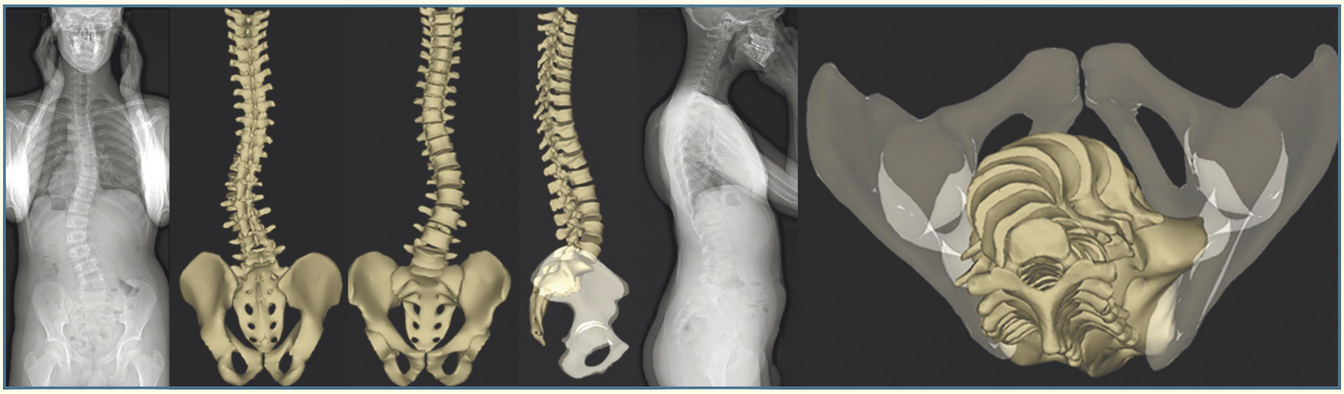

**Fig. 2**
3D reconstruction by EOS equipment

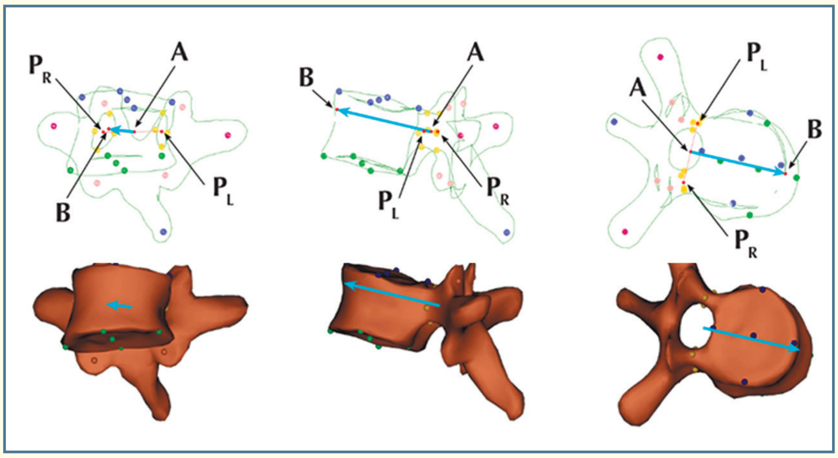


**Fig. 3**
Quantification of vertebral deformity in horizontal plane: vertebral vector by Tamas Illes, Jean Dubousset, Szabolcs Somoskeoy (2009)

examination due to the deformity severity index developed by Wafa Scalli and her engineers at the laboratory of biomechanics at ENSAM in Paris. This index is based on the Cobb angle value, with the most important fact being that it is also based on the torsion index (apical axial rotation, intervertebral rotation at the superior and inferior pedicles of the arch, apical lordosis). All these indicators characterizing deformity in the frontal plane comprise the formula for predicting scoliosis progression. In case of 0.4 index value, scoliosis is regarded as a non-progressive, while in case of 0.6 it is undoubtedly progressive. For example, comparison of the two arches with 10° Cobb angle allows regarding one of them as progressive and the other one as non-progressive upon their alignment in the horizontal plane (top view). In this plane, torsion is determined better than using conventional spine radiographs.

I have also proposed the spinal penetration index (Fig. 4, 5), which characterizes a change in the chest shape due to penetration of the vertebral bodies into its cavity in lordoscoliosis. This phenomenon can be easily studied using 3D reconstruction of the thoracic spine. That is the reason why an original corset (3D-brace) comprised of flexible twisted carbon fiber bands was created by craftsman Gerald Dauny in France. These bands are attached to the front part of the corset leaving the back open. The exact application of these twisted bands enables development of the horizontal force providing real detorsion and kyphotization of the thoracic spine due to muscular effort during normal or forced breathing. Control over the effect of corset therapy is provided by 3D reconstruction of the spinal column.

When we assess degenerative scoliosis with a vast kyphotic component corrected by using PSO with the help of EOS, we note excellent correction in all of the three planes. However, we do not have an answer to the question: what happens to the balance? It can only be assessed during movement: walking, climbing the stairs and etc. In order to speculate on the presence or absence of balance, a 3D surface reconstruction of the skeleton from head to toes, registration of the foot pressure on the special force platform, 3D recording of body and spine segment movements, including head and pelvis, using several video cameras are needed. As a result, the cone of economy and dynamic balance of the patient can be estimated.

In this aspect, the three elements are in constant connection: alignment, balance and stability. Balance (in static or dynamic) should be regarded as stability in motion. It should be comprehended both for the body as a whole and for an individual vertebral motion segment, primarily for "disc – true joints" complex. However, one should never forget that global and local balances are constantly interconnected. Deterioration of one of them in order to achieve compensation is possible. Therefore, one cannot be ignored while correcting another one of them. The best example are reoperation cascades after a simple intervention for disc herniation with formation of localized lumbosacral kyphosis.

At local level, alignment and balance are automatically related to the problem of "stability – instability". I define immediate instability as excessive amount of motion between two segments of the spine on functional spine radiographs requiring early stabilization in order to prevent spinal cord injury. On the other hand, potential instability cannot be determined through spine radiographs but it may develop abruptly as a result of minimal trauma (often with serious consequences) or slowly over time (months and years) due to the vertical load and minimal movement. A typical example is progressive rotatory dislocation (Fig. 6), which is formed at the transition level of degenerated spine (usually at L3–L4) when an unstable disc is subjected to shearing and dislocating impact. Examination of disc structures by micro-CT method demonstrates the interconnections between elastin and fibrillin tissues via transverse crossbridges (Fig. 7).

At global level, vertical position (upright or sitting) is characterized by three basic elements.

1. Balance circuit, which acts as an inverted pendulum. There is a supportive polygon for both feet at the bottom, then goes the skeleton of the lower extremities, pelvis as a sole pelvic intercalary bone (pelvic vertebra between the body and lower extremities), 24 vertebral motor segments, and, finally, head or cephalic vertebra. Oscillations at the top of the balancing circuit provide stability of horizontal gaze. Noteworthy, that, during evolution of quadrupedal animals, foramen magnum turned out to be displaced dorsally on the skull by integration into the vertebral chain, while it was displaced ventrally in chimpanzees, Australopithecus, Pithecanthropus and homo sapiens. Thus, the more bipedal hominids became, the more displacement to the central part of the skull was noted for the foramen magnum. The idea of cephalic vertebra becomes apparent during examination of a growing child who suffered multiple cervical-thoracic laminectomy surgeries with subsequent development of swan neck-type deformity, which is the result of continuous efforts for maintaining the horizontal gaze. Another example

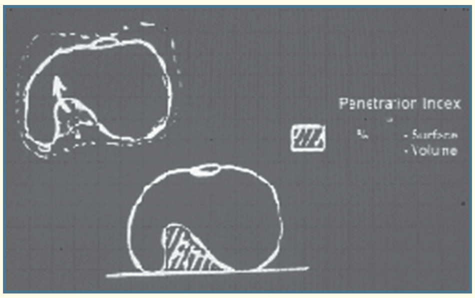

**Fig. 4**
Dubousset penetration index: formation of the inner hump

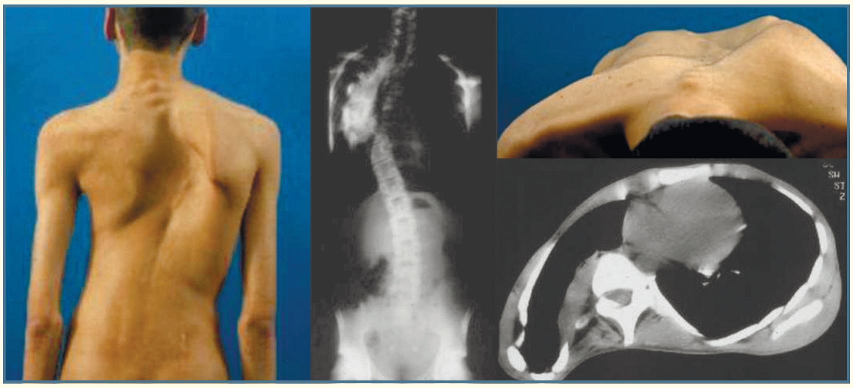

**Fig. 5**
This is the how it looks clinically and in cross-sections of the chest

is a patient with congenital muscular dystrophy, who applied to my clinic with severe hyperlordosis, which forced him to support hindhead constantly with his hand. After correction of the spinal deformity, his head was completely balanced, and his hands were free. This is the proof of the concept of inverted pendulum (head weight ranges from 4.5 to 5.5 kg and averages 7 % of body weight). It should be noted that the area of a foot support is 80 $cm^2$, the area of both feet is 160 $cm^2$, while the projection of body gravity center when there is a distance between the feet never presents a single fixed point, since there are always some malalignments, which are different in direction and amplitude within an irregular circle, demonstrating the fact that there are constant oscillations even at rest.

2. In accordance with the posture (sitting or upright), there are different ways to compensate for the kyphotic or lordotic spine deformities in anterior or posterior inclination of the pelvis: a function of the pelvic vertebra, which plays the role of the intercalary bone providing adaptation to the spinal deformity, especially of the lumbar region. The role of the sacrum manifests itself during walking through characteristic oscillations both in the transverse plane and in the frontal plane, which was called "pelvic step" by Ducroquet brothers.

3. Finally, the economy of energy due to the cone of the economic concept. I described it in 1975. This is the concept of the minimal use of muscular energy for maintaining a vertical position, i.e. a situation where the skeleton regions aligned at the joint level so that the passive tension of the fibrous capsular structures of the joints and passive tension of postural muscles allow active muscles to perform minimum work, which is demonstrated by EMG. It was also shown by Pol Le Coeur for the skeleton completely devoid of muscles, which was present in a vertical position for 1/100 seconds with two rubber imitators of the frontal regions of the capsule of both hip joints and strings stretched between the calcaneus and the posterior femoral condyles due to the correct position of the head, spine and pelvis. Therefore, when a person's body is located inside a small cone, minimum muscle function and maximum stability are provided by vertebral structures or tools, and prognosis for the unit formation is favorable. If the body is constantly located outside this cone, muscles function constantly, which leads to fatigue and permanent overloads with maximum risk of endocorrector fracture in the spine and regions of implanted tools.

*Acquisition and development of vertical posture in humans.* Unlike most quadrupeds who develop the ability to stand and, often, walk immediately after birth, in humans, this function develops gradually over months and sometimes takes a year or more. It is the result of harmonious formation of bones and joints, which are stable during movement due to the development of the neuromuscular system based on automatic reflexes and voluntary modulation providing balance. Moreover, the beginning of the process is accompanied by innumerable falls. We can say: "Children learn to walk by falling while the elderly falling stop walking". The development of bipedal locomotion correlates with the development of balance. It begins with the first attempt of the baby to raise its head in the prone position, when it turns to the right and to the left. During the first 14 months, the process continues (from the head to the feet) involving all regions of the locomotor system: crawling position, then upright position with support and without it. Two months after transition to standing, pelvis position is stabilized. Then, in the period of 14 months to 6 years of age, the development spreads from the feet to the head, hip joints stabilize, head and thoracic girdle function as a unit. At the age of 7–8 years, balance organization with the vestibular dominant continues downward. In the period of 8 to 13 years, organization takes place in both directions, while complete dissociation of the head and torso is achieved in adulthood. Walking is a sequence of forward falls prevented by automatic ventral movement of the lower extremities. A look from the top to

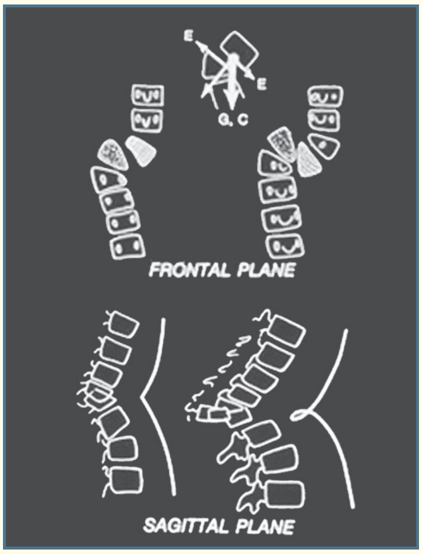


**Fig. 6**
Rotatory dislocation: kyphosis between two lordoses

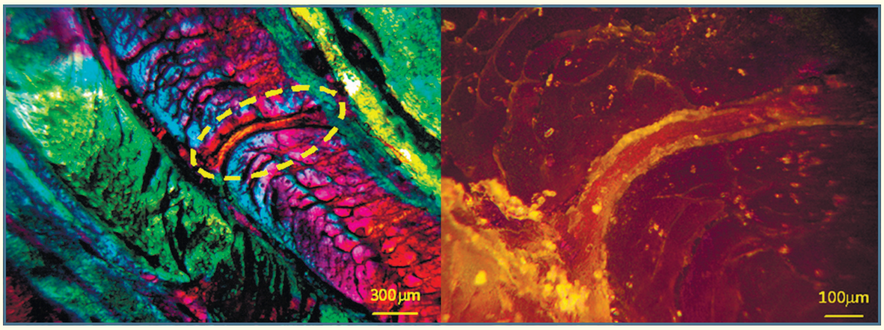


**Fig. 7**
Crossbridges between elastin and fibrillin tissues of the disc

bottom allows determining pelvis movement in the horizontal plane. The angle between the foot and the surface, pace, and the speed of movement are quantitative criteria of this basic function.

What is balance? In reality, it is a biological function based on the basic principle, signal and its consequences: perception, integration, modulation, and action. The signal itself can be of various nature: electric, piezoelectric, thermal, chemical, hormonal, and molecular. All processes in the body are connected with balance: glycemia, immunology, ACTH/cortisol, heart rate, sleep, i.e. almost everything! Where does it come from? First, it appears at local, then global levels. From my point of view, there are three main books devoted to this problem: “Physiology of the movement” (Duchenne, 1867), “The body axis” (Andre Thomas, 1948), “The Balance Within: The Science Connecting Health and Emotions” (Esther M. Sternberg, 2001). The principles of “signal – reaction – action” work at the level of all joints. The receptors are located at the level of the skin, tendons, muscles, ligaments, joint capsules, and bony structures. Impulse is transmitted in both directions through the peripheral nerves, roots, synapses, neural pathways of the spinal cord and brain. Modulators are located in the brain, cerebellum, brainstem nuclei, thalamus, hippocampus and hypothalamus. Finally, there are effectors that act on joint capsules, ligaments, muscles, tendons, and skin. The balance mechanism requires vestibular system, proprioception, and the presence of integrative modulating centers (oculomotor and somatic) in order to achieve body stabilization and eye gaze.

Just think for a moment: what is required for such an easy movement as climbing the stairs with a package in hands? First, there are mechanical conditions: mobility of the joints, passive and extra-articular balances, real chain of joints in the space. The second one is muscles: agonists-antagonists, strength, relaxation, modulation, speed, acceleration, and deceleration. The third one is the nervous system: afferent vision, ENT (Eyes, Nose, Throat), semicircular channels, proprioception, modulation, coordination, automatism, effectors, transmission speed, and reaction speed. The fourth is the formation of these components of the real spatial chain.

An example for understanding is the upper limb: shoulder joint (orientation and stabilization); elbow joint (remote adaptation); wrist joint (regulation, orientation, stabilization); fingers (proprioception, performance of a specific task). What a great coordination in space: one-sided or double-sided!

Thus, the first important conclusion is that the general balance of the human body in three-dimensional space is provided by the function of the nervous system.

The second main conclusion is that the clinical experience indicates that imbalance is often compensated automatically (knee flexion in different leg length, hyperlordosis in flexion contracture of the hip joints, shoulder abduction in disrupted forearm pronation).

For example, aging leads to the weakening of active extensors of the hip joints followed by pelvic retroversion, compensatory flexion of knee joints and lumbar kyphosis: all of this is necessary for balance restoration (stability during motion). Virtually, the loss of hip joint extension (called the extension reserve by Istvan Hovorka) is the equivalent of flexion contracture (anteversion of the hip joint) and has two consequences: 1) joint replacement in many cases solves the problem of back pain, since it allows the joint to compensate for a moderate loss of lumbar lordosis; 2) it explains many failures of the spinal fusion surgery with sacral fusion (in the near and long-term periods).

Morphology of the pelvic spine and its inclination angle (pelvic incidence) are individual, each person has his own morphotype (form) of the spine, especially it includes sagittal contour of the spinal column. It (contour) was described and classified by Roussouly, who introduced a slight slope (types 1 and 2 with a slight lumbar lordosis) and a large slope (types 3 and 4 with larger lordosis; Fig. 8). Thus, there is a genetic factor in the chain of factors providing body balance.

In order to demonstrate an important role of the pelvic vertebra in compensation processes, we studied 30 patients with idiopathic scoliosis operated on as juveniles in the thoracic spine (spinal fusion at a maximum level of L1–L2) and compared the results with a group of healthy adolescents. The amount of motion was measured using a “Vicon” 3D system with external markers and EOS system (3D X-ray). We found changes in pelvis position and increase in the amount of motion in 18 patients, 9 patients had no changes, while reduction was noted in 1 case. Change in pelvic incidence was observed in 50 % of cases. All of this is the result of automatic adaptation, which demonstrates the compensatory possibilities of the pelvic spine (Spine. 2006. N 20. Vol. 31. E359–366).

Body balance is not just a matter of angles, kyphosis, lordosis, slopes, and etc. It is also a matter of the three-dimensional pile of body mass (head, thorax with the upper limbs, abdomen, pelvis) relative to the gravity line. Disregard of this fact explains some failures of large-scale vertebral surgeries justified only by calculation of projection angles, because such approach does not take into account the compensatory possibilities. If we take as an example the extended fusion (T2 to sacrum) with transpedicular osteotomy for severe frontal inclination of torso, we can observe magnificent restoration of the sagittal contour on control spine radiographs, but we cannot obtain any information regarding body balance until the patient starts walking.

The problem is that balance is the result of complex multilevel interactions of the body systems: afferentation (vision, proprioception), integration (CNS, spinal cord, brain), effectors (almost all muscles), and nervous system (conduction velocity). Therefore, it is extremely important to evaluate active mobility prior to surgery, primarily in order to avoid suppression of possible compensatory regions. There are two examples of such strategy. The first is a patient with the consequences of polio; stabilization and balance are achieved only by extension of the fusion zone to the sacrum with a long-term observation period. The second is a case of congenital myopathy, when the previously performed spine fusion with sacral fusion led to the formation of ventral imbalance, which required bilateral pelvic osteotomy in order to normalize body position. This is the reason why I presented a new concept at the conference in Miami in 2011: the spine as a statue with mobility only at the cervical-thoracic level and hip joints. This situation creates a high risk of PJK formation due to induced spinal imbalance at the level of cephalic vertebra formed in severe lumbar hyperlordosis or hip joint pathology. Upper transition kyphosis immediately after correction of spinal deformity is not a matter of hooks-screws-wires-ligaments-connectors (Fig. 9). It is a matter of local balance of cephalic vertebra. There should be a clear understanding of the "balance curcuit" concept. Why is this superior transition kyphosis (fracture, instability) formed? Because preoperative planning was based on radiographs or 3D reconstruction in static! The amplitude of the segmental mobility (both active and passive) above and below the future unit, as well as extension reserve in the hip joints was disregarded. The corresponding weight of the head, thorax, abdomen, pelvis, and lower extremities should be taken into account.

If we go back to the basics of biomechanics (weight, effort, torque), it should be taken into account that the vertebral segment can withstand the load of 3000 to 6000 Nm in case if it acts on the center of the vertebral body, but in its ventral displacement of 10 cm, the load that can be withstood decreases to 10–20 Nm. Therefore, with age, when kyphotic deformation increases, the risk of vertebral body fracture or tool-associated problems increases. The loads on each motor segment caused by kyphotization have been studied by Carl-Eric Aubin from Canada (Spine Deformity. 2015;3(3):211–218) who once again demonstrated the value of the concept of the cone of economy. We are very committed to the measurement of angles! One should remember that initial studies on baricentrometry conducted by Duval-Beaupere et al. (1987) and earlier by Clauser (1969) showed that the head weight comprises 7.3 % of the total body weight, while hands comprise 5.2 %, body, hips and tibia are 50.0 %, 10.8 % and 5.8 %, respectively.

Three-dimensional study of segmental masses and torques for each vertebral-motor segment is no less (if not more) important

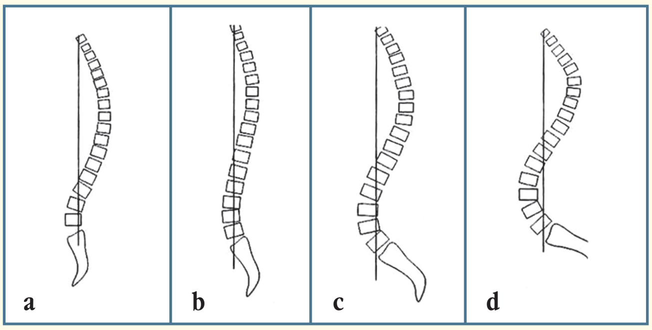


**Fig. 8**
Sagittal morphotypes of the spine by Roussoly: **a** – type 1; **b** – type 2; **c** – type 3; **d** – type 4

than angle measurement when determining body 3D balance. Nowadays it can be performed without any problems using an EOS system due to external measurements with automatic determination of the outer contours and the subsequent localization of the gravity center for each segment. A high degree of reliability, 2 to 10 mm, can be achieved by comparing these data with those obtained by using a gravitational platform. However, if we take a look at the head position relative to the gravity line, we can see that it is a very variable statistical parameter that ranges from person to person, since the gravity center should be positioned over the femoral heads, while staying at the same time at the gravity line. The head weight acts as a pendulum in the balance circuit as demonstrated by my friend Dick Gross, who used the posterior rib captures in the treatment of severe thoracic kyphosis in growing children.

A 3D dynamic study (with external markers) was carried out in the laboratory in order to enable prediction of evolution in time, but it required sophisticated equipment. Combination of EOS system with gravity platform and data of dynamic 3D examination with external markers allowed determination of dynamic balance in space and evaluation of pre- and postoperative picture (angles and weights). Moreover, it also allowed assessment of an elderly person spine from the perspective of the cone of economy.

Preoperative study of motion amplitude at the segment level (sagittal balance) and assessment of muscle function in upright and prone positions: flexion – extension at the cervical spine, shoulder girdle and the superior thoracic region, thoracolumbar region, lumbosacral junction and, of course, hip joints. This is how possible adaptation/compensation of each segment is achieved. All of this is controlled by profile spine radiographs.

Thus, prevention of PJK depends on the four factors:

1) examination should not be limited to the transitional vertebra of the superior structural arch;

2) examine active posterior flexion of the two elements: head and cervical spine plus thoracic region of the spine with scapulae (including humeral heads);

3) examine sagittal contour of the lumbar and thoracolumbar regions of the spine: in case if the lumbar region is not planned to be fused in the unit – identify active lumbar lordosis, in case if its fusion is planned – measure the rate of lordosis and pelvic incidence;

4) possible extension in the hip joints (active and passive).

Often, all of these types of examination cannot be carried out in practical clinical work. A simple, reproducible, objective and quantifiable method of measurement (e.g., chronometer) is required. In some way, it might be more reliable than the popular questionnaire on life quality.

Here, I propose the methods that I always use in my clinic during pre- and post-operative examination:

1) speed of walk over a distance of 5 meters back and forth;

2) speed and ease of movement on the stairs: 3 steps upstairs and 3 steps downstairs;

3) speed and ease of squatting and getting up (most demonstrative);

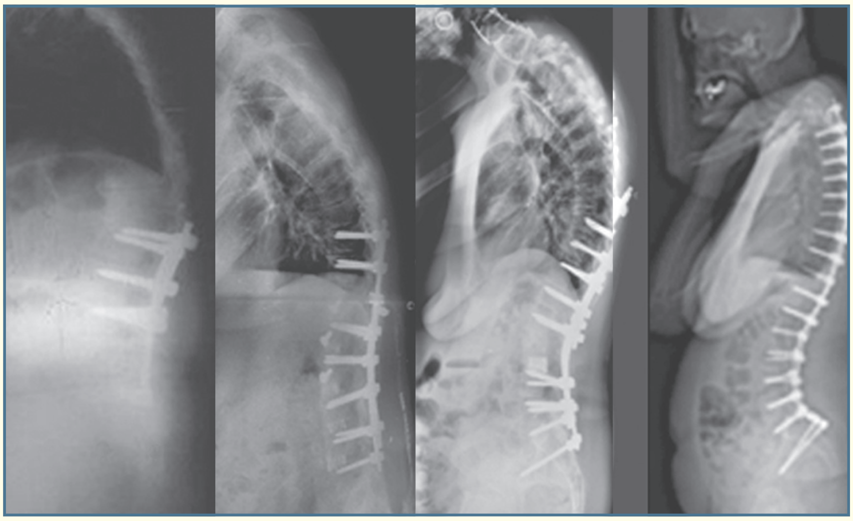

**Fig. 9**
Why is kyphosis formed? Because the surgeon disregards amplitude of segmental active and passive 3D mobility prior to surgery

4) speed and ease of walking while simultaneously talking on the phone (double task).

For me, the dynamic balance in space is the key to the longevity of the vertebral segment.

Spine with degenerative changes is often subjected to repeated sequential dorsal interventions (discogenic Cascade), which reduce the compensatory possibilities of vertebra, disrupt dorsal muscles, and the spine becomes like a statue. Why not follow in this situation the suggestion by Gilles Norotte of intervention at discs 2–3–4 through a small ventral access?

The balance includes the following: 1) the state of bones and joints (shape, mobility, mechanical strength); 2) muscular strength (volume, relaxation and deceleration speed, trophism); 3) adequate command-coordinating afferent connection (vision, the vestibular system, proprioception, modulation, coordination, automatism of double task, and etc.).

Prevention of imbalance involves a lot of factors (risk factors are active at the age of 45–60): 1) nutrition, vitamin D, proteins, possible orthopedic correction, including surgical intervention; 2) daily exercise sufficient in time and intensity, but not in the type; 3) monitoring and adjustment of view, personalized shoes, exercise, cognitive rehabilitation double task; 4) careful drug administration.

Exercises

1. Standing on one leg, eyes open, hands on chest, horizontal look at a single point (red) at the level of eyes.

2. Double task: throwing of the ball from one hand to the other with gaze accompaniment.

3. Similar to the first exercise, but with eyes closed, time is fixed using chronometer.

Results for the two groups (with and without exercise). An increase in implementation time of the third test, 5 to 30 sec, is noted after 3 months of training. Does the age at time of the beginning of exercises effect their outcome? Patricia Dargent-Molina (2013) conducted a meta-analysis of 17 papers (mean age, 76 years): 2195 people performed exercises every day (Tai Chi and balance exercises) and 2110 people had no exercises. Result: there are 40 % less falls and 61 % fewer fractures in the group with exercises. The conference on the muscles at the French medicine academy (13 January 2015) showed that satellite cells are able to increase and restore muscles: 45–65 divisions at the age of 5 days, 28 divisions at the age of 15 years, 17 at the age of 31 years, and 15 the age of 80 and 85. Thus, muscle recovery can be achieved by exercises even at the old age.

## Conclusion

Alignment and balance are not opposed but complement each other. Good alignment is preferred for good balance, but it is not enough.

Alignment should be examined in 3D from head to toes (but not only on the radiographs of the whole spine) as a common balance circuit. Compensation should be regarded as follows: passive at each level (motion in the joints – amplitude), it becomes active due to the loop (reaction, the optimal afferentation, sensitivity, proprioception, integration, spinal cord, cerebellum, brain, recognition, effectors (muscles, tonus, speed). Result – balance!

Farcy and me tried to understand and quantify the human balance in all of its components (mechanics, hearing, vision, emotions, the vestibular system, proprioception, thalamus, hormones, muscles) at the balance study Fund for prevention or correction of age-related changes.

Good health in old age is prepared in the childhood.

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

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*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.*