SELECTED LECTURES

ON SPINE SURGERY

WHY IS A 3D IMAGE OF THE WHOLE SKELETON USEFUL IN TREATING SPINAL DEFORMITIES?

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The lecture discusses in detail the issues related to the EOS system, which allows scanning a patient's skeleton from head to feet in two standard projections with x-rays perpendicular to the surface they reach. At the same time, the radiation load is reduced by a factor of 10 compared with routine spinal radiography. The EOS system is unique: simultaneous 3D study with image acquisition in any plane, including a top view, gives a real three-dimensional assessment of the spine or its deformity. Further, it is possible to carry out measurements in all planes and in all directions. To quantify spinal deformity in three planes using EOS, the Vertebral Vector Projection program has been developed. The principle is the replacement of each vertebra with an anteroposterior vector starting dorsally at the midpoint between pedicles, reaching the midpoint of the ventral surface of the vertebral body and running parallel to its cranial end plate. Thanks to the capabilities of EOS, the severity index was developed — a formula based on x-ray data. For small deformities (less than 15°), the Cobb angle, the torsion index of the curve, axial rotation of the apical vertebra, intervertebral rotation at the upper and lower ends of the curve, and apical lordosis are taken into account. The value of the index varies from 0 to 1. If it does not exceed 0.4, the deformity will not progress, and if it exceeds 0.6, the deformity will increase in 100 % of cases. The geometric and mechanical personified 3D model allows preoperative planning for severe deformities: it helps in choosing the level and direction of the section, the magnitude of the resected angle, and in computer modeling of the closure of bone surfaces to obtain a new type of spinal alignment. The EOS imaging system helps to understand the need to distinguish between alignment (statics) and balance (dynamics) of the spinal column.
Key Words: spinal deformity, EOS system, three-dimensional space, 3D image, diagnostics.
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Actually, this concept is very old, but it was implemented in practice only after the creation of the so-called EOS system (the first version dates from 2000). At a good moment, the meeting of researchers from three fields of knowledge, probably very distant from each other, once again demonstrated that co-operation of clinicians and scientists is the best way to progress.

The first group consisted of G. Charpak (Fig. 1) and his team, who developed a low-dose X-ray detector (replacing photons with electrons) that allowed acquisition of digital images at an X-ray radiation dose reduced by a factor of 10.

The second group included biomechanical engineers from the Ecole Nationale des Arts et Metiers (ENSAM) in Paris, primarily Fr. Lavaste and W. Skalli, who created computer and mechanical 3D models of the human skeleton using the finite element method. J. De Guise from the Laboratoire de Recherche en Imagerie Orthopedique in Montreal helped in solving the automation issues.

The third group included doctors from the St. Vincent de Paul Hospital in Paris, a radiologist G. Kalifa and an orthopedist J. Dubousset. The latter proposed the pelvic vertebra concept in 1972 and the balance chain and cone of economy concepts in 1975.

It should also be recalled that in 1977, we together with an orthopedist H. Graf and a computer engineer J. Hecquet worked on 3D reconstruction of the spine in health and scoliosis (Fig. 2). For this, we successfully used X-ray radiography with the patient in a standing position, in standard anteroposterior and lateral projections. We were able to demonstrate the importance of evaluating the spinal column shape using a top view on the stacked vertebrae, which was much closer to three-dimensional reality in comparison with 2D projections (shadows) provided by radiography.

EOS system

The device can scan the patient's skeleton, from head to feet, in two standard projections using X-rays transmitted through a unit producing parallel X-ray beams (collimator) that are always perpendicular to the body surface. For this, two important requirements should be met (Fig. 3):

1) a strictly defined position inside the EOS cabin: a horizontal gaze using a mirror moved to the eye level; the fingers of both hands are on the cheeks to prevent superimposition of humerus shadows on the upper thoracic vertebrae; a very small forward displacement of one foot relative to the other to exclude superimposition of the lower limb shadows during computer reconstruction and distinguish between symmetrical points of the right and left limbs;

2) full immobility during the entire scanning time (15–18 s) to prevent artifacts during reconstruction; if needed, the patient

can sit on a chair; in a standing position, a stabilometric platform can be used.

Significant reduction in the radiation dose. Scanning of the patient's entire skeleton in two projections is accompanied by a 10-fold decrease in the radiation dose compared with that of routine spine radiography. The obtained data were used to generate computerized 3D reconstruction model of the patient's entire skeleton. The radiation load of CT scans for three-dimensional reconstruction of the entire skeleton amounts to 43 mSv, while that of a similar EOS examination is 0.05 mSv, i.e. less by a factor of 860. Currently, application of the microdose system to examine the entire skeleton causes a 7-fold decrease in the radiation dose, which is significant from the orthopedic surgeon's viewpoint.

While the daily natural radiation is 6 µSv (63 µSv per week), one EOS examination in two standard projections is equivalent to the weekly natural radiation, which is 45-fold less than one ordinary radiograph.

Amount of acquired information. First of all, we obtain two-dimensional images of the entire skeleton in the physiological standing position, which enables measurements, starting from the gravity line projection, and accurate evaluation of the distance to reference points on the joints and skeleton bones in the frontal and sagittal projections. This is not affected by any distortions due to constant orthogonality of X-rays relative to the screen. This is particularly important for determining the spine position relative to the plumb line orthogonal to the center of the support area using reference points – the odontoid process C2 or a projection of the sella turcica that, in turn, is located close to the head's center of gravity. These images are very useful in determining alignment of the lower limbs.

Then, we create 3D reconstruction of the entire skeleton or its part, e.g., the spine, from the head to the middle third of the lower limb, including the entire pelvic vertebra with both femoral heads, which are the main landmarks for many spine-related measurements. There is an opportunity to focus on more specific elements that are particularly important for the orthopedic surgeon: the lumbosacral junction, hip joints in various positions (sitting, standing, tilting), or shoulder girdle.

Significance of gravity. The significance of gravity becomes apparent when we compare 3D reconstruction of the lumbar spine using CT in the supine position with 3D reconstruction using EOS in the standing position (the same patient with adult scoliosis). The quality of both images is identical, but the rotational dislocation at the L3–L4 level is more clear and pronounced in the EOS-based reconstruction, probably due to vertical loading.

Why is CT-based 3D reconstruction sometimes dangerous for children and young adults? CT images provide great opportunities for examination of transverse body sections at a single level, but understanding of three-dimensionality of spinal deformity requires multiple consecutive sections at different levels. This examination is reasonable in the case of local pathology, such as congenital hemivertebra, for planning resection surgery. But CT examination of the

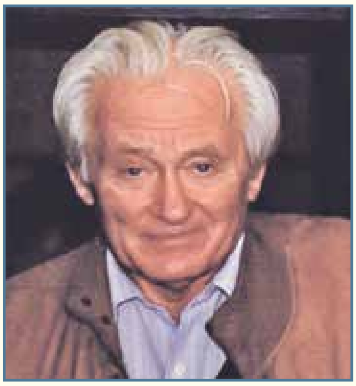

Fig. 1
Georges Charpak (1924–2010), 1992 Nobel Laureate in Physics

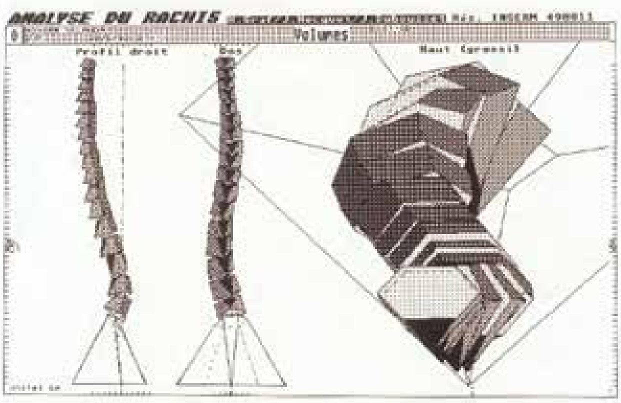

Fig. 2
3D reconstruction of the spine in health and scoliosis (J. Dubousset, H. Graf, J. Hecquet)

entire spinal column, even providing high-quality images (not always useful for both the patient and the surgeon), is unacceptable for the child and young adult patient because of the risk to induce malignancy, which has been confirmed by many authors.

A clear increase in the breast cancer incidence rate was noted in scoliosis patients after numerous chest radiographs.

A Danish publication (2016) reported the data that the incidence rate of breast and endometrial tumors was 5-fold higher in scoliosis patients 25 years after termination of X-ray studies than in the general population.

The incidence rate of cancers in adults increases 1.62-fold after a single CT examination of the body in childhood. According to Australian researchers, who examined 680,000 children and adolescents, a single CT examination increases the risk of genital organ tumors in adulthood by 24 %. The risk of leukemia increases 3.18-fold when the patient is exposed to a radiation

Fig. 3
Three-dimensional image of the human skeleton obtained using an EOS machine

dose of 5 to 30 mGy. The risk of brain tumors increases 2.82-fold at the total dose in a range of 50–74 mGy.

Some aspects of practical application of the EOS system

Pathology of bones and joints of the upper and lower limbs. EOS replaces many classic examination techniques (e.g., pangonograms) that remain only shadow projection techniques, but without magnification or distortion due to the orthogonality of X-ray paths. EOS also replaces CT examination because it enables assessment of rotational abnormalities, bone length differences, etc. EOS provides accurate assessment of the position of hip joint components and the acetabular depth. This is three-dimensional examination of the knee, ankle, shoulder, elbow, and wrist joints, additional capabilities to study their kinematics, and, of course, most diverse applications in the field of endoprosthetics at any level, from preoperative planning to postoperative assessment of the outcome.

A unique system for examination of the spinal column. Simultaneous 3D examination with acquisition of an image in any plane, including the so-called top view, provides real three-dimensional assessment of the spine condition or its deformity (Fig. 4). This top view is unique because it is a horizontal plane projection of each vertebra and its elements, each of which has its own 3D position in space relative to the patient's weight-bearing line. Further, we can take measurements in all planes and directions: sagittal, frontal, and horizontal. To facilitate identification of the vertebrae, each region can be assigned a color: blue for the thoracic spine, red for the lumbar spine, and white for the cervical spine. We should learn to read these projections and spare no time for measuring frontal and sagittal deviations, the angle and magnitude of the distance from the weight-bearing line, as well as axial rotation, including intervertebral rotation. Of course, multiple measurements are burdensome. On the other hand, it is important for the surgeon to assess the condition of blocked and non-blocked parts of the spinal column and give them 3D assessment. In ordinary postoperative radiographs, our eyes are primarily focused on the implant; in this case, the state of unblocked parts can be difficult to assess, while their reconstruction using EOS provides great information.

To simplify the analysis, visualization, and quantitative assessment of spinal deformity in three planes (primarily in the horizontal one) using EOS, the Vertebral Vector Projection software was developed. This was done by a Hungarian orthopedist Tamas Illes with assistance of a computer engineer Szabolc Somoskeoy. The principle is replacement of each vertebra with an anteroposterior vector that starts dorsally at the midpoint between pedicles, reaches anteriorly the midpoint on the ventral surface of the vertebral body, and runs parallel to the cranial end plate of the vertebra. Therefore, the length of this vector is determined by the length of the vertebral body. In the frontal plane without rotation, this vector is represented by a point, but as the axial rotation increases, its length increases, reaching the maximum when the axial rotation is 90°. In turn, in the sagittal plane, the vector retains its full length if the axial rotation is 0°, reducing to a point if the rotation reaches 90°. Naturally, in the horizontal plane, the vector length does not change depending on the axial rotation, and the angle between the vector and the reference line is directly proportional to the lateral displacement. Therefore, the position of this vector is most easily analyzed using an axial projection, from the top of the spinal column (Fig. 5). This enables evaluation, at a glance, of the pre- and postoperative condition of the spinal column in scoliosis. Next, we can measure the surface created by linking starting point projections with respect to reference lines of each curve and compare the pre- and postoperative condition to determine the percentage of deformity correction, because the surface is equal to zero in the normal spine. On the other hand, the possibility of an axial view enables assessing the difference in the direction of vectors of two vertebrae and determining the exact localization of the transition between different segments of the deformity. In other circumstances, the choice of a lower instrumented vertebra is based on the capability to examine intervertebral rotation in the horizontal plane, identify an unstable level, and usually include it in the fusion area to prevent secondary changes, imbalance, and pain recurrence.

Examination of intervertebral rotation enables easy identification of an unstable vertebra in the scoliotic spine and, upon conservative treatment with a plaster cast or brace, especially in the case of a lumbar curve, localization of this point to start treatment as early as possible and prevent rotational dislocation (intervertebral rotation in opposite directions at the two adjacent disc level), which completely depends on the condition of soft tissues of the spine.

The prediction of deformity progression at first examination: severity index. The classic approach to choosing a treatment option for idiopathic scoliosis is as follows: after revealing a structural curve with a small Cobb angle, it is recommended to wait until new radiographs show deformity progression. For me, this is nonsense, because deformity progression is accompanied by pathological changes in all soft tissues (discs, ligaments, etc.) as wedging of vertebral bodies and degenerative changes in synovial joints increase. This prompted our team to develop a reliable marker for the risk of deformity progression, which may be used at the patient's first visit and first examination. By using the EOS capabilities, ENSAM engineers developed a formula based on X-ray data, especially upon examination in the horizontal plane, which was called the severity index. In small deformities (less than 15°), the Cobb angle, curve torsion index, axial rotation of the apical vertebra, intervertebral rotation at the upper and lower ends of the curve, and apical lordosis are considered. The index value varies from 0 to 1. If it is not more than 0.4, deformity does not progress; if it is more than 0.6, the deformity increases in 100 % of cases (Fig. 6). In our group of 77 patients, the index showed progression in 71 (92 %) patients, which was observed in all cases. Having this information, we believe that waiting for progression is simply a waste of time, and treatment should be started as quickly as possible, even if the Cobb angle is 10°; in this case, a night brace should be used, which provides hypercorrection of deformity and full correction of the torsion.

In addition to 3D spine reconstruction, the EOS skeleton imaging system reconstructs the thoracic cage, which provides new opportunities. Reconstruction of the thoracic cage (ribs, sternum, and appropriate cartilage) requires special software but demonstrates a high degree of reliability, even in significant deformities. There is the capability of measuring the thoracic cage in three planes, sometimes with simple linear modeling of the spatial position of the ribs. This enables a reliable visual examination of, e.g., the brace effects on the shape of the ribs. Hemithorax volume measurements were made, which demonstrated a higher accuracy level compared with CT data. This technique enables easy measurement of the spinal penetration index (the thoracic cage volume occupied by the vertebrae, which is 10 % in the normal condition, 25 % in moderate scoliotic deformity, and 50% in severe scoliosis; Fig. 7). The chest wall and thoracic cage volume are also measured with a great accuracy: the accuracy of correlation between the volume and pulmonary function tests achieves 0.001. It is very interesting to use the EOS system in the top view projection to evaluate the shape of the spine and thoracic cage before and after brace therapy. Evaluation of the brace therapy effectiveness in relation to the shape of the spine and thoracic cage shape and volume is an important point for brace manufacturers because this makes it possible to fix the brace immediately if the result is not optimal.

On maturation of bone structures and soft tissues (discs, ligaments, capsules, and aponeuroses are almost ignored). Numerous studies have been devoted to assessing the degree of bone and cartilage maturation, from childhood to adulthood. There are many atlases for estimating bone age using the hand, elbow and shoulder joints, pelvis, and spine. These data were compared with sexual development stages and chronological age. As noted in studies by Alain Dimeglio,

Fig. 4
Top view provides real three-dimensional assessment of the spine condition and its deformity

Federico Canavese, and James Sanders, all comparisons were completely reliable. Surprisingly, but there have been a few, if any, reports on life-long maturation of soft tissues (disc capsules, ligaments, aponeuroses, and even muscles) that are anatomically and functionally associated with the spine! We well know how they change with age, and how degenerative changes develop in them, but it is not so easy to define "completion of growth" because the picture should be supplemented with many clinical symptoms. For example, when brace therapy is interrupted, there are always a lot of obscurities. For example, it is believed that Risser test 4 or 5 means height growth completion, and brace therapy can be terminated. In reality, a number of researchers (Stephane Wolff from France in the 1980s and Toru Matuyama from Japan in 2015) have demonstrated that brace therapy started at Risser test 4 or 5, especially in lumbar deformities, can reduce the Cobb angle by 5° and retain this result for three years. For me, this is somehow associated with maturation of soft tissues, collagen, and connective and elastic structures. Whether the concept of tensegrity is applicable to the vertebral structures? Tensegrity (stress-bound structure) is sufficient compression/extension of mobile elements to achieve stability. This is a function of the white structures (aponeurosis, ligaments) named by Fancois Bonnel who attached great importance to automatic release of energy in maintaining the body position and making automatic movements. This is another reason to recall the importance of early detection, even in the slightest deformities, of initial manifestations of rotational dislocation (intervertebral rotation in opposite directions at the level of two adjacent discs).

The EOS skeleton imaging system in everyday practice, unfortunately, is often used for 2D examination. Why? Because three-dimensional reconstruction is not yet adopted by everyone and takes time to be understood. Nevertheless, research laboratories have developed numerous clinical applications of the method.

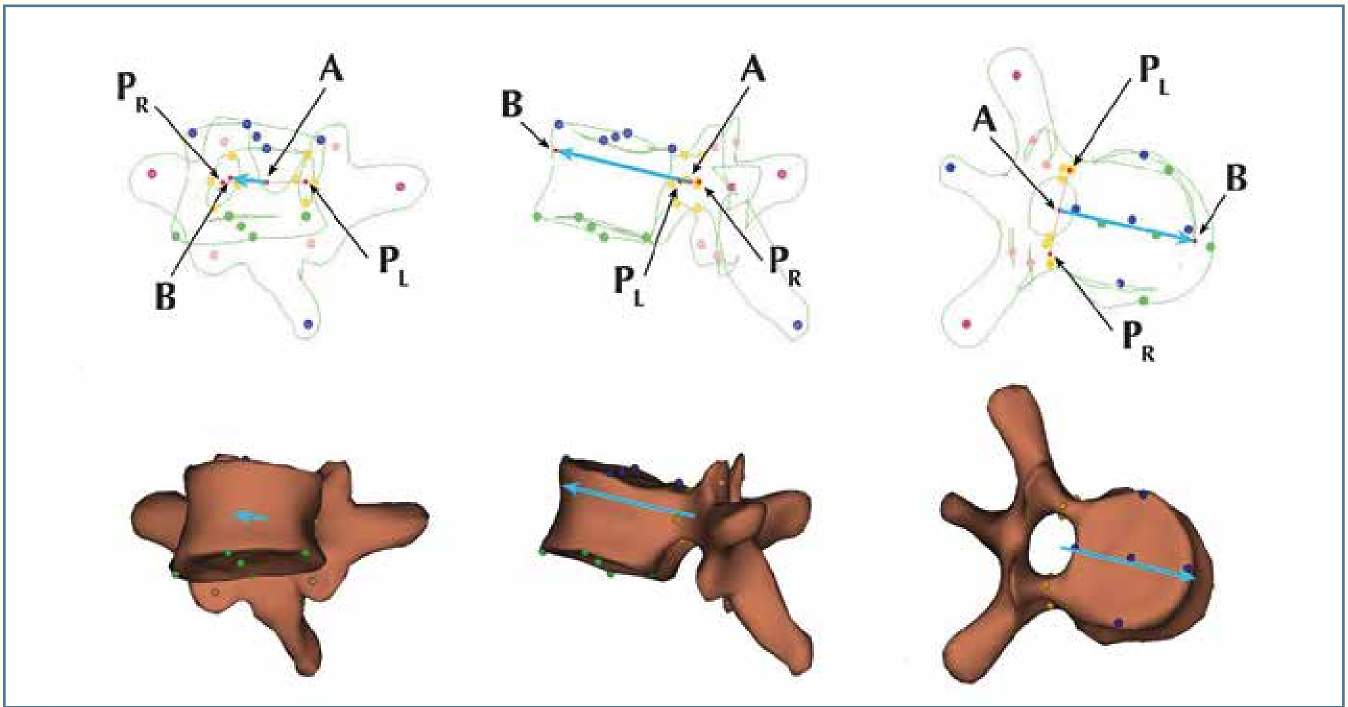

Fig. 5
Quantitative 3D-assessment of spinal deformity using EOS technology (vertebral vector)

A geometrical and mechanical personalized model of intervention simulation. Positioning of the patient on a traction operating table is simulated using CD instrumentation after entering data including spinal mobility determined using functional radiographs. In the case of right thoracic scoliosis, a rod is first implanted to the concave side, and a derotation maneuver is performed; then, a rod is implanted to the convex side. In the case of left lumbar scoliosis, a rod is first implanted to the convex side and rotated; then, a rod is implanted to the concave side. We obtained results with a high degree of reliability in terms of compliance with the real clinical situation. We can simulate alternative approaches by changing levels of the upper and lower instrumented vertebrae in the computer and testing the result in frontal and sagittal planes as well as alignment of the segments of non-instrumented spine regions. This enables choosing the best strategy for each particular patient.

Preoperative planning in severe deformities requiring radical interventions (transpedicular osteotomy) and postoperative evaluation of outcomes. We begin with creating a three-dimensional EOS model of the spine, chose the level and direction of resection and the magnitude of the resection angle, and simulate closure of bone surfaces using the computer to produce a new type of spinal alignment. This virtual operation can be performed many times if the surgeon is not satisfied with the result. The projection from the spine apex (top view) is also useful and used before and after surgery, but the body balance can only be assessed in the clinic, when moving and functioning.

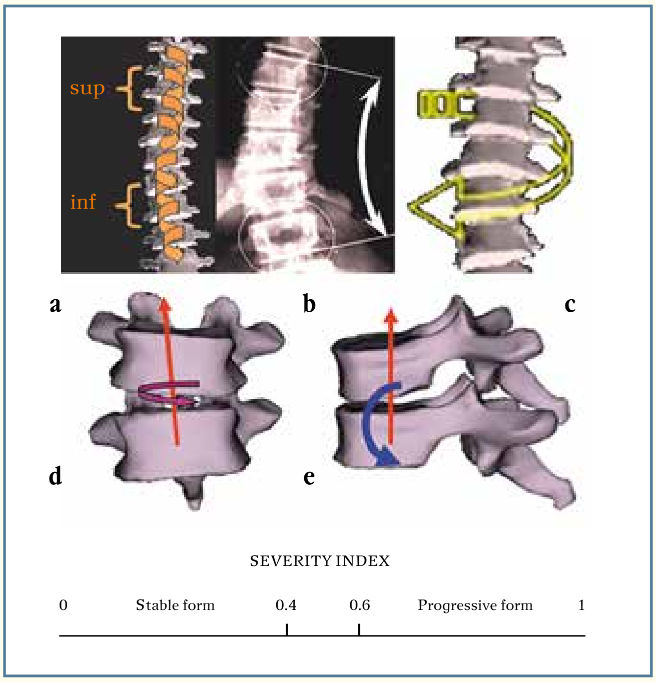

Fig. 6
Determination of the deformity severity index: with allowance for torsion index **(a)**, Cobb angle **(b)**, apical axial rotation **(c)**, intervertebral rotation at curve ends **(d)**, and apical lordosis **(e)**

The EOS imaging system helps understand the need to distinguish between alignment (statics) and balance (dynamics) of the spinal column. Overlapping static and dynamic analyzes by overlapping EOS images and external markers for motion analysis is a good examination tool. For this, an EOS image is combined with external analysis in statics and dynamics using 3D markers glued to the skin at reference points and monitored by six cameras in a precisely calibrated area.

The results of a comparative study of idiopathic scoliosis surgical correction using CD instrumentation in study and control groups (30 patients of the same age in each) were published in 2006 (Spine. 2006, May 20;31:E359–366). We demonstrated that the pelvic vertebra is an important compensatory factor for the patient's automatic adaptation to new statical and dynamical conditions. An unexpected result was an increase in the pelvic incidence angle up to 18° in 50 % of the cases (from 5 to 18° in 4 cases, from 7 to 14° in 6 cases, and unchanged in 11 cases). The conclusion is obvious: the pelvic vertebra is an important factor in automatic compensation in the patient's standing position and in dynamics. These measurements at regular times enable evaluating the rate of changes and the possibility of compensation in elderly patients. For example, annual examination of the sagittal balance and full spine extension demonstrates that limitation of extension increases every year, despite the use of a brace or physiotherapy. There may arise a question about surgical treatment (if indicated) to prevent serious cardiorespiratory dysfunctions.

This laboratory examination using modern 3D assessment methods is suitable for very complex cases and special patients. However, in everyday clinical practice, we need simpler but more reliable examination methods. Personally, I use four simple tests with a chronometer to assess the time required to complete the following exercises:

– get up from a chair and walk forward five meters and then walk backward;

– climb three steps and go back;

– perhaps, the most discriminating exercise is to squat and get up;

– walk a few meters, talking on the phone or counting backwards from 100 to 90 (this option helps assess the presence of cognitive impairments).

Using these simple tools, we can evaluate not only the dynamics of functional capabilities of the elderly patient but also the functional result of surgical treatment. In my opinion, these tests are more objective and reliable than questionnaires.

The EOS system in body weight examination. When we talk and think about the statics and dynamics of the human body, we are sometimes too focused on projected angles, even when working with EOS, while forgetting a little that when examining the whole human body, we need to think about its weight. That is why, after we integrated the stabilometric platform into the system, evaluation of soft tissues surrounding the skeleton by inspection and measurement has become part of the EOS system. Automatic detection and 3D reconstruction of the external contours are performed together with positioning of the gravity center of each spinal segment, thereby enabling automatic personalized barycentremetry for each spinal segment. Comparison of stabilometry and EOS data showed a difference of 1 mm to 1 cm.

Fig. 7
Spinal penetration index: the thoracic cage volume occupied by the vertebrae

Comparison of the general skeleton picture with the soft tissue covering of the trunk, surface topography, or optical picture shows a good correlation. Therefore, one day, a simple smartphone picture will become a satisfactory non-invasive method of postoperative follow-up, eliminating the need for radiography.

Importance of the horizontal plane projection for assessing trunk alignment and balance. Isidor Liebermann from Dallas attempted to quantify the concept of the cone of balance and was able to measure a projection displacement of the body center of gravity onto the floor in a patient in the standing position, without movement. In reality, it was clear that this projection constantly moved from right to left and more often from front to back to achieve a balance described as "stability within movement". Simultaneous percutaneous electromyography demonstrates the important role of pelvic and gluteal muscle movements in controlling the standing function. On the other side of the globe, a Japanese researcher, Kazuhiro Hazegawa, showed an easy way to visualize and digitalize this body position by projecting the entire body, including the head, onto a horizontal plane from the top view. Perhaps, in the near future, this approach will replace measurement of the Cobb angle in spinal deformities, which, in fact, reflects only spine collapse.

Many other capabilities of the system, mainly in laboratory examination. Mechanical models and anatomical specimens studied using the EOS system and 3D reconstruction can be compared with the data of clinical studies. This can be done, e.g., upon examining the cervical spine (dynamic study: flexion, extension, rotation, etc.) or the hip joint before and after replacement surgery. An attempt to relate the findings and measurement results to the MRI data enables personalization of 3D muscle examination with the use of various volumetric indices, isotropic or elastic index, volumetric evaluations of contractile, non-contractile tissues, adipose tissue, etc. Another application is the determination of the bone density index necessary in testing for osteoporosis (risk of fracture of the vertebral body or femoral neck in the elderly).

Conclusion

The low-dose EOS imaging system is designed to examine the human body in three-dimensional space, in particular in the horizontal plane in the physiological standing position. It provides tremendous research opportunities. Unfortunately, across the world, this tool is used to evaluate the spine in only two planes, and we hope that in the near future, the medical community will appreciate the EOS system and begin to use it for 3D reconstruction of the human skeleton.

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