Cone of Economy with the Chain of Balance—Historical Perspective and Proof of Concept

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Abstract:

A bipedal erect posture with a horizontal gaze is a distinctly human characteristic. The standing mechanism was described by Jean Felix Dubousset in the early 1970s as the "*cone of economy*," in which the axial skeleton is aligned in balance with the feet, lower limbs, and pelvis (*pelvic vertebra*) to the spinal segments, ending with the cranium (*cephalic vertebra*). All the components act in concert, allowing for adaptive motion in all directions on the horizontal plane. In a normal subject, the body maintains balance within a small "cone" using minimal muscle activity, and in a subject with pathologic lesions of the locomotor system, maintaining a standing posture requires a larger "cone" and greater muscle activity. Evidence from recent studies using the EOS imaging system, force plate measurements, surface electromyography, and full-body reflective markers with surface electromyography have gradually consolidated the "*cone of economy*" concept, a fundamental hypothetical theory of human locomotion.

Keywords:

alignment, balance, cephalic vertebra, cone of economy, pelvic vertebra, spine, standing, three-dimensional evaluation

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Introduction

A striking characteristic of the human locomotor system is the bipedal activity in daily life by which man has achieved an evolutionary apex. In the standing posture, the axial skeleton aligns in balance, starting from the feet; lower limbs with ankle, knee, and hip joints; pelvis; and spinal segments, ending with the cranium. All the components act in concert, which is figured as a "cone" in which the gravity line of the body lies within the center of the surface, allowing equal motion in all directions of the horizontal plane. A normal subject can maintain balance within a small cone with minimal muscle action, whereas a subject with a pathological lesion of the locomotor system acts within a larger cone with muscles working at their maximum level to maintain balance. This concept is now widely known as the "*cone of economy*," first proposed by coauthor Jean Felix Dubousset (JFD) in the early 1970s (Fig. 1A)[1)].

The neuro-musculoskeletal components of the whole body work together to realize standing balance, termed the "*chain of balance*." The body (polygon) is sustained by the "chain" comprised of key components: the feet, pelvis (*pelvic vertebra*), and the cranium (*cephalic vertebra)* (Fig. 1B). In the aging spine with decreasing lumbar lordosis, the thoracic spine becomes flattened, the pelvis becomes retroverted, and the knees flex to maintain a standing posture with a horizontal gaze[2)]. In a patient with spinal deformity, three-dimensional (3D) alignment of the lower limbs, especially knee flexion, improves following spinopelvic correction surgery[3)]. Such a compensatory phenomenon is realized involuntarily by the *chain of balance*[4)]. "The human body as an engine made by the hands of the Lord, is incomparably better organized and, regarding his movements, more admirable than those invented by humans" (translated by JFD)[5)].

The purpose of this article is to describe the historical perspectives of the concept of the *cone of economy* with the *chain of balance*, and to offer recent evidence regarding standing alignment and balance in relation to this concept.

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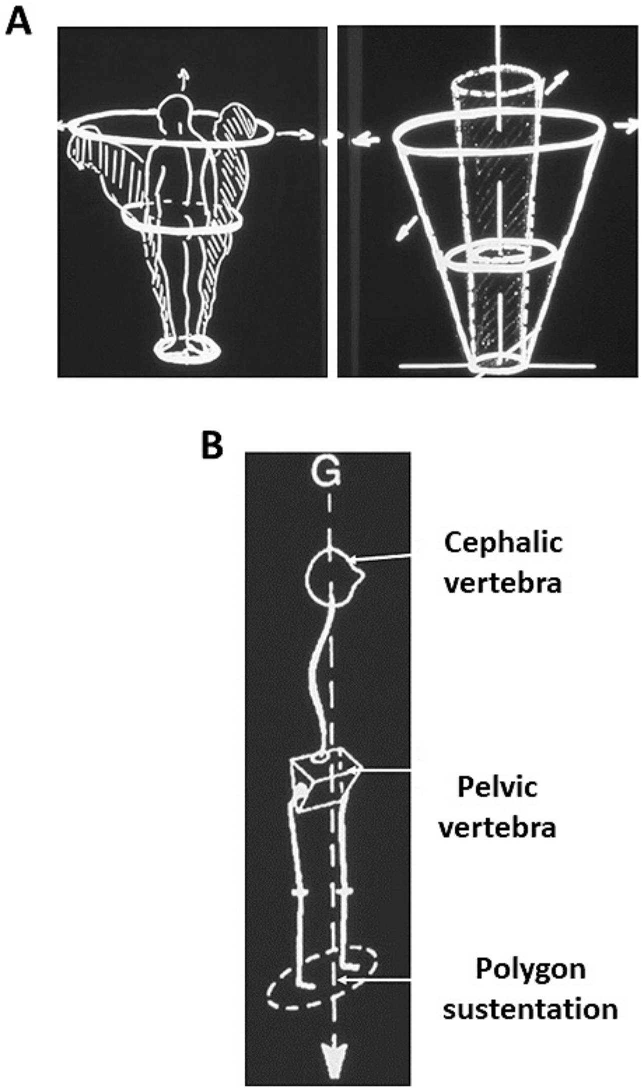

Figure 1. Concept of the *cone of economy* (A) with the *chain of balance* (B).

I. Three-Dimensional Understanding of the Alignment and Balance of the Spine

JFD treated many patients with spinal deformities for more than 60 years. In the early phase of his career, an 11-year-old boy with paralytic spinal deformity due to poliomyelitis gave him insight (Fig. 2A). The patient could not even sit independently because of paralysis from the trunk to lower limbs. X-rays showed severe spinal deformity with pelvic obliquity. Traction X-ray demonstrated correction of not only scoliosis, but also pelvic obliquity and vertebral rotation (Fig. 2B). During the course of treatment, JFD realized that scoliosis is 3D spinal deformity, and traction force realigned all the components, including the pelvis (Fig. 3). The pelvis is an intercalary bone at the base of the spine, and, thus, when performing a radiological examination of patients with deformity, the pelvic orientation should be revised to the true anteroposterior position in the horizontal plane, and then fit to the cranium[6,7] and feet in coronal and sagittal planes. Depending on the condition, the orientation of all the vertebrae in relation to the pelvis can be determined quantitatively (Fig. 3).

Scoliosis and kyphosis are determined using two-dimensional (2D) images in the coronal and sagittal planes, respectively. The true shape of deformities involving scoliosis, kyphosis, lordosis, and rotation of vertebrae, however, must be determined using 3D images. It is important to remember that X-ray film provides only a shadow of a 3D structure, and the true 3D shape must be captured (Fig. 4). Although 2D analysis using conventional X-rays is widely used clinically, the images differ from the true 3D shape. The gap between the shadow image and the true shape must be minimized. JFD and his colleagues began 3D visualization of all the vertebrae using computerized analysis in the early 1980s[8]. Subsequently, a remarkable collaboration among multidisciplinary partners (radiation engineers in physics, engineers in biomechanics, medical radiologists, and orthopedic spine surgeons) led to the development of a new slot-scanning 3D X-ray imaging system (EOS), (EOS Imaging, Paris, France) that overcomes the limitations of conventional X-ray measurement. The default scan speed of EOS is 7.6 cm/s. The acquisition time is linked to the scan height: time of acquisition (s) = height of acquisition (cm)/ 7.6. Thus, subtle artifacts in the images can occur due to body sway during scanning, but the artifacts are minimized by the rapid X-ray detection time (0.8333 ms) with no blurring of the images. These advances are attributed to Georges Charpak, who received the Nobel Prize in 1992 for his development of the Xenon multiwire proportional chamber that amplifies the signal of low-dose primary X-rays to produce a high-quality digital radiograph[9].

EOS allows, with significantly lower X-ray exposure than the usual X-ray system, the simultaneous acquisition of coronal and sagittal views of the standing whole body, with a scanning technology that performs undistorted 1/1 scale acquisition in a standing posture. Using the two slot-scanning X-ray acquisitions (coronal and sagittal), anatomical landmarks are first manually identified on the pelvis, allowing for identification of the true patient sagittal plane (a truly sagittal pelvic plane) and the radiological plane. A slight rotation of the pelvis can have an impact on the 2D measurements of the pelvis performed with usual X-ray systems. Following computation with matching the pelvis in the radiological plane to that in the patient (true pelvic) plane by rotating with 3D volume data, measurement of all parameters in the true sagittal pelvic plane becomes possible. The alignment parameters obtained via EOS are measured from the 3D volume data in which the pelvis is in true anteroposterior orientation in the horizontal plane, i.e., 3D measurement.[2,9-11] In an investigation with a total of 60 asymptomatic subjects (ages 20-81 years), the subjects were measured twice each by two new observers following training. Intraobserver and interobserver reproducibility and similarity of the sagittal spinopelvic parameters were compared between 2D and 3D measurements. The intraclass correlation coefficient was very high for the 3D measurements (>

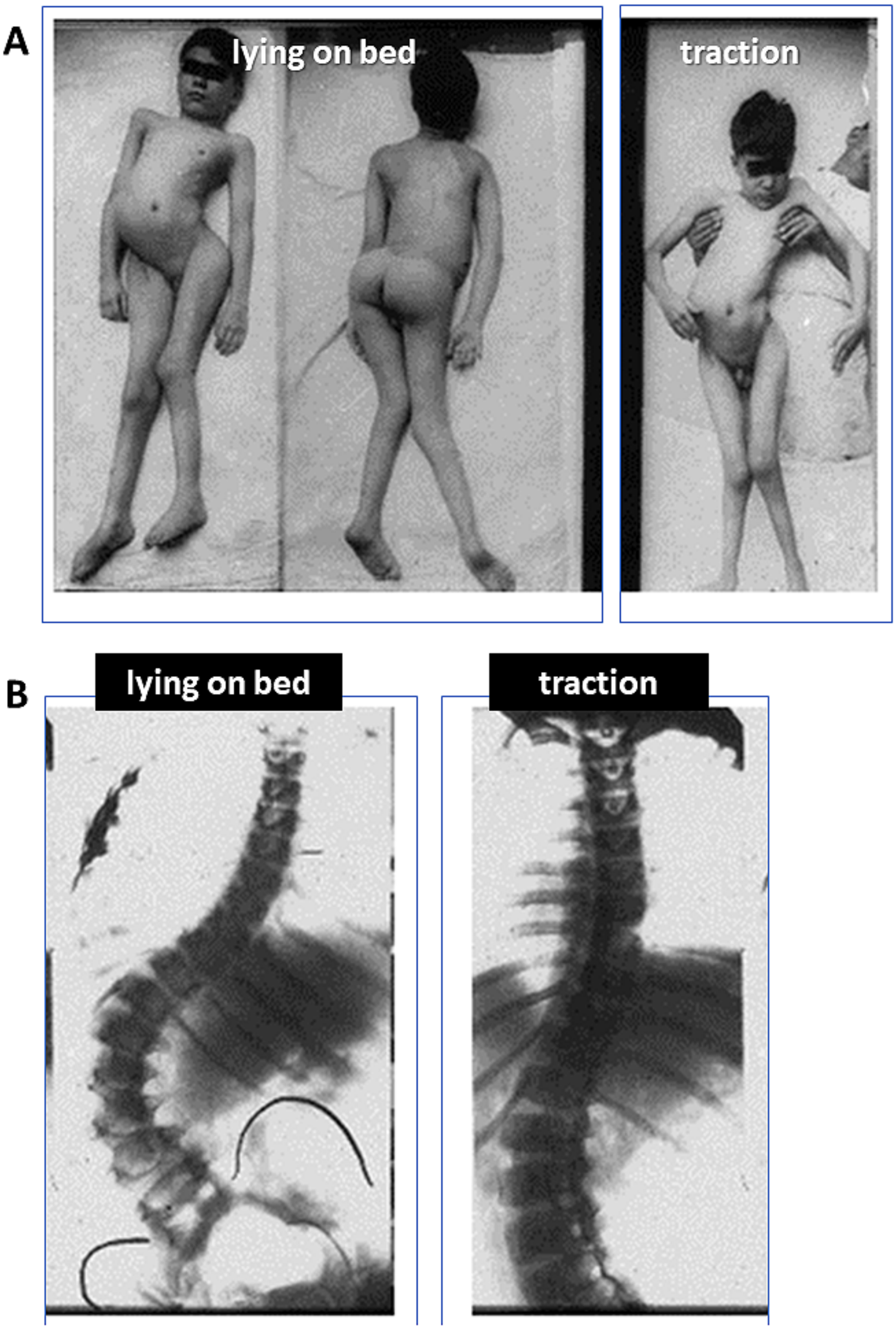

Figure 2. An 11-year-old boy, paralytic spinal deformity due to poliomyelitis. Photos on the bed (A) and X-rays (B).

0.9) and excellent for the 2D measurements (>0.75). In all cases, the overall mean absolute difference between repeated 3D measurements was less than 2° or 2 mm. For all parameters, the interobserver and intraobserver reproducibility in 3D measurements were significantly superior to 2D measurements ($p<0.03$). Hence, 3D measurements have better reproducibility than 2D measurements for sagittal alignment[12]. EOS is a crystallization of JFD's dream.

EOS is valuable especially in the evaluation of a case with adult spinal deformity in terms of whole body alignment before and after surgical treatment. A 71-year-old woman who suffered from mechanical low back pain with radicular pain to the left limb for more than 5 years was referred for treatment. She was thoroughly evaluated and diagnosed with degenerative kyphoscoliosis with multilevel lumbar foraminal stenoses (Oswestry Disability Index [ODI][13]= 51.1, Scoliosis Research Society—22 revised [SRS-22r][14]= 2.0 in subtotal score). EOS imaging revealed decompensated malalignment[4] in the coronal, sagittal, and horizontal planes, LL=3°, PT=31°, PI-LL=43°, knee flexion=10° with scoliosis (Cobb angle=38°), and remarkable C7 off-set with vertebral rotation=12° at the apex (Fig. 5A-C). We performed decompression, correction, and fusion surgery from T9 to the pelvis. The postoperative course was uneventful. At 2 years postoperatively, she had no disability in activities of daily living (ODI=9.0, SRS-22r=3.5], and the corrected 3D align-

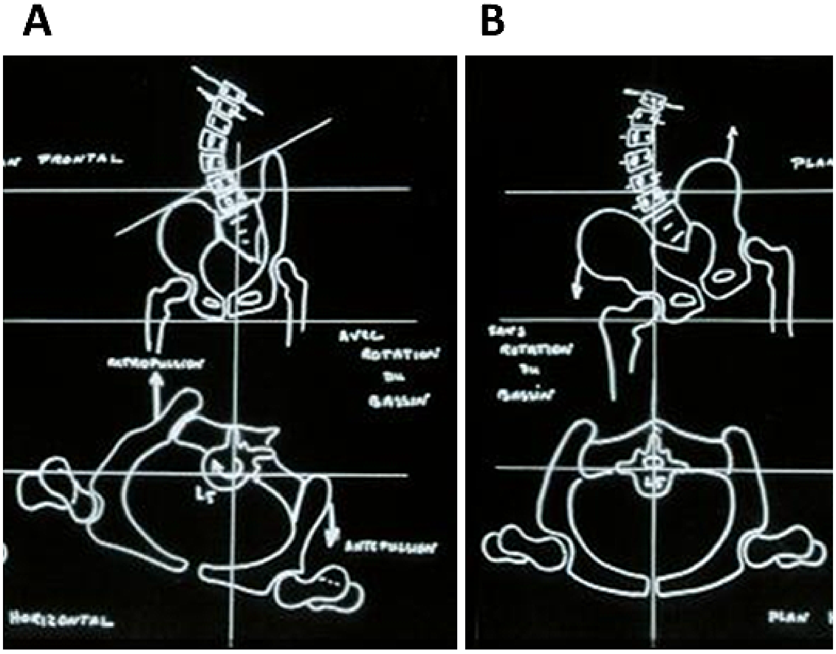

Figure 3. Descriptive projections of coronal and horizontal planes of a scoliotic patient with pelvic obliquity and rotation (A). Once the pelvic rotation is revised in the horizontal plane, the figures are significantly different (B).

Figure 4. A bronze statue with spinal deformity and the shadow.

ment in the standing posture was well maintained (Fig. 5D-F).

To investigate the relationship between three grades of sagittal compensation for standing posture (normal, compensated, and decompensated) and health-related quality of life (HRQOL) measurements, we analyzed a total of 50 healthy volunteers, 100 patients with single-level lumbar degenerative spondylolisthesis, and 70 patients with an adult to elderly spinal deformity using the SRS-22r and whole body alignment parameters with EOS. On the basis of cluster analysis of the SRS-22r subscore, the pooled subjects were divided into three HRQOL groups as follows: almost normal (mean 4.24, SD 0.32), mildly disabled (mean 3.32, SD 0.24), and severely disabled (mean 2.31, SD 0.35). All the alignment parameters differed significantly among the cluster groups. The threshold values of key alignment parameters for the severely disabled group were TPA>30°, C2-7 lordosis>13°, PI-LL>30°, PT>28°, and knee flexion>8°[4]. Hence, evaluation of 3D whole body standing alignment is indispensable for diagnosing patients with spinal disease, especially adult patients with spinal deformity and more or less whole body compensation. Presently, imaging of 3D whole body standing alignment is only possible using EOS.

II. “Cephalic Vertebra”

Humans have a broad vision in standing posture thanks to the wide range of craniocervical motion. The alignment of the segments changes according to the direction of the vision. Vision, however, is disturbed when the craniospinopelvic alignment deteriorates. A 6-year-old girl with a diagnosis of intramedullary neuroblastoma was treated by tumor resection through total laminectomy from C3 to T3, resulting in severe swan neck deformity (Fig. 6A-C). The cranium is at the top of the “pendulum” of the *chain of balance* (Fig. 1). The head is estimated to weigh between 4.5 and 5.5 kg, which burdens each segment of the laminectomized spine, whereas the patient intends to maintain vision in the horizontal direction during daily living, driving kyphotic force to the cervicothoracic segments and lordotic force to the upper cervical segments. The repeating force to

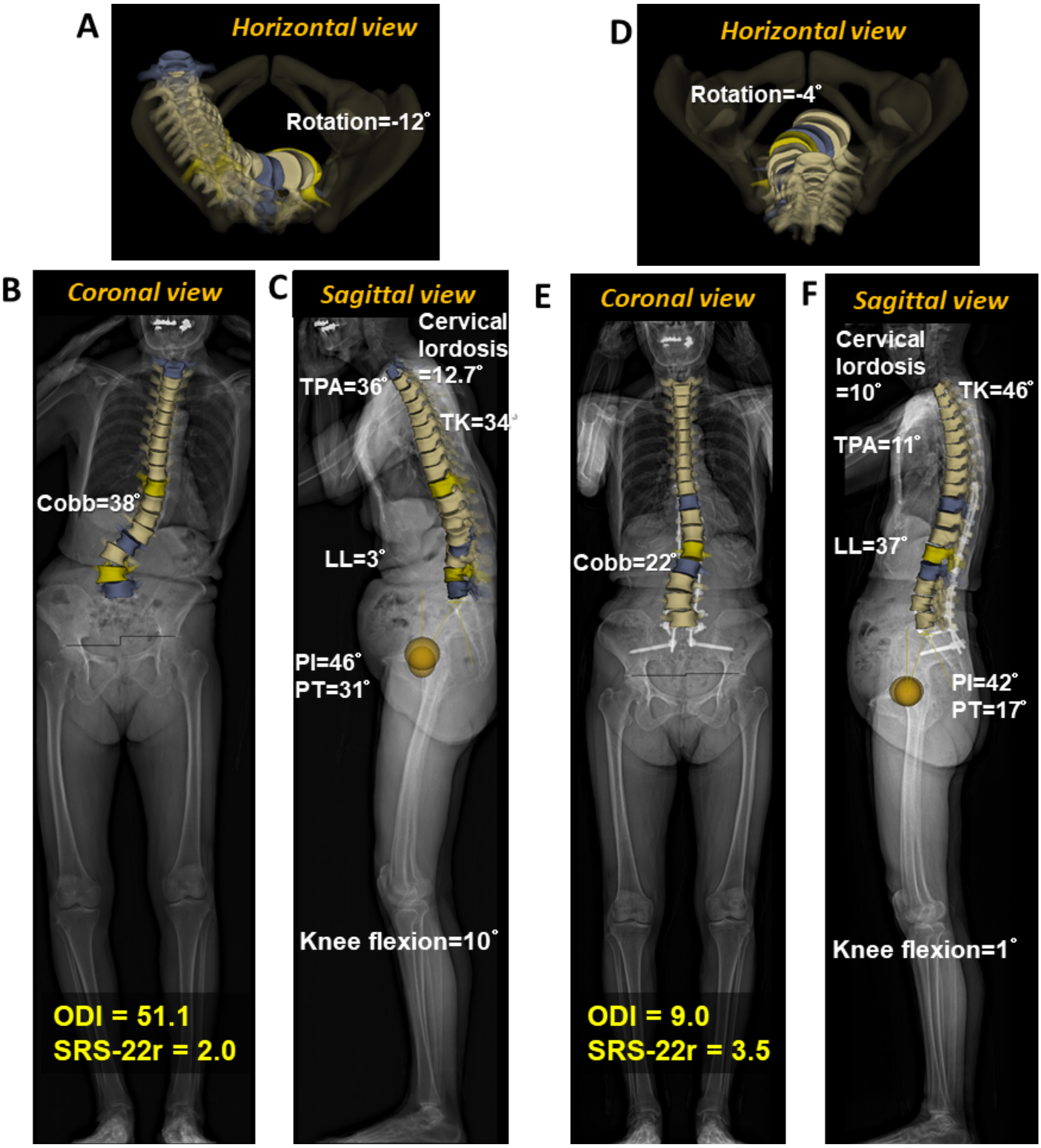

Figure 5. A 71-year-old woman with degenerative kyphoscoliosis and multilevel lumbar foraminal stenosis. EOS images before surgery: horizontal (A), coronal (B), sagittal view (C), and EOS images postoperative 2 years: horizontal (D), coronal (E), sagittal view (F).

the flexible cranio-cervicothoracic region during the growth period might induce swan neck deformity (Fig. 6D).

A 12-year-old girl with spinal lordosis due to congenital muscular dystrophy was referred for treatment. Her appearance and X-rays showed whole spine lordosis from the cranium to the pelvis. She could not maintain her head position for a horizontal gaze, and always held her head with her hand (Fig. 7A). A surgical correction and fusion to restore sagittal alignment was performed using CD instrumentation. The cranio-cervicothoracic sagittal alignment was corrected. The natural standing posture was restored and she obtained a horizontal gaze without any assistance by her hand. The position of the entire head (cephalic vertebra) and the spinopelvic alignment were recovered within the *cone of economy* (Fig. 7B).

These two cases of craniocervical malalignment with vision disturbance demonstrate the strong functional relationship between cranium and the spine. Hence, JFD termed the cranium as the “cephalic vertebra” in 1971. Cephalic vertebra implies that we must pay attention to the alignment and balance of the head as a part of the whole body when evaluating and treating a patient with spinal deformity.

Recently, Stenlund et al studied 20 healthy male subjects (18-43 years) on a movable platform seat delivering 15 side-

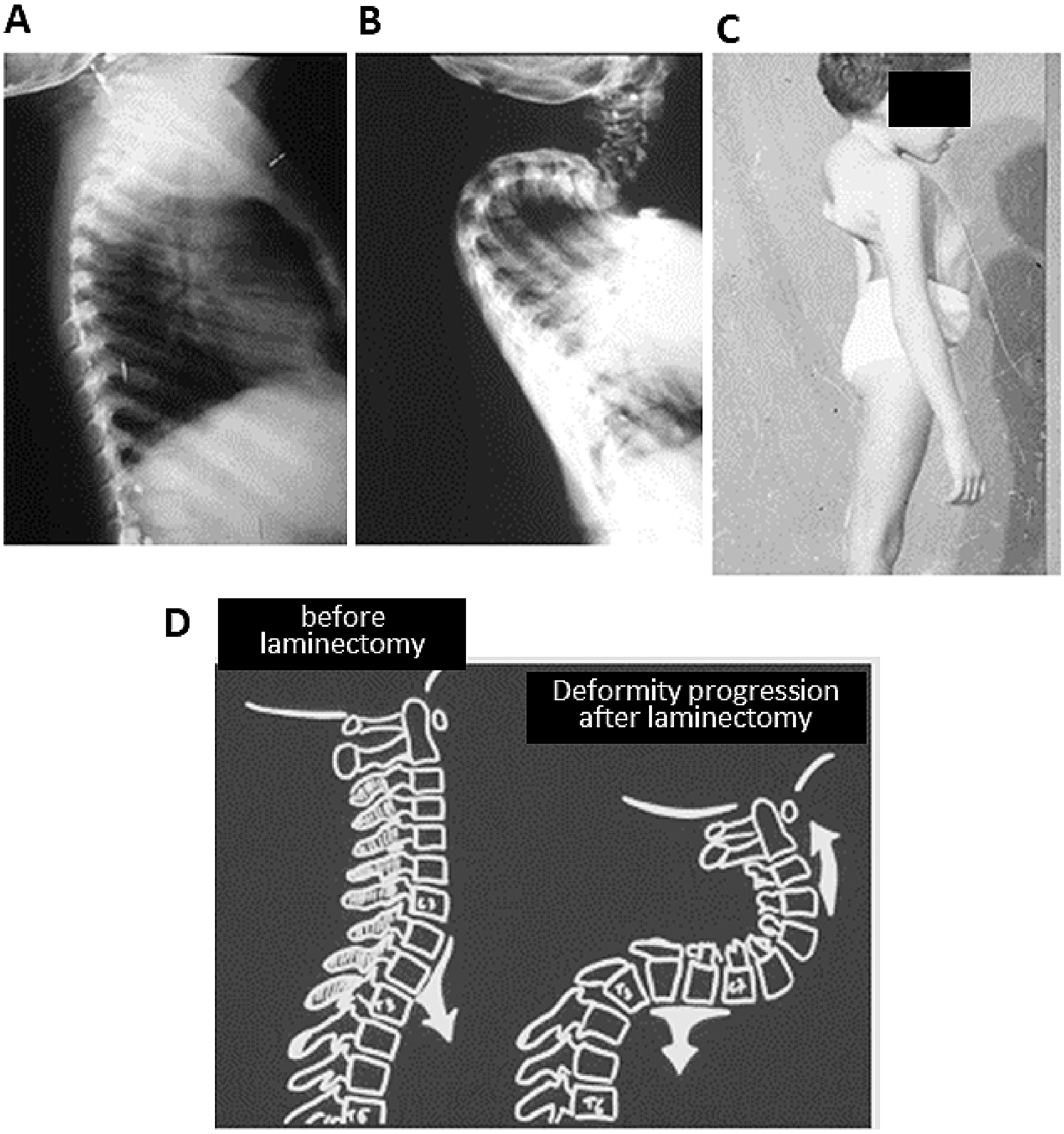

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Figure 6. A 6-year-old girl with a diagnosis of intramedullary neuroblastoma was treated by tumor resection through total laminectomy from C3 to T3 (A), resulting in severe swan neck deformity (B, C). D: progression mechanism of the sagittal malalignment (D).

ways perturbations while holding their head in a neutral or laterally flexed posture. Surface electromyography (EMG) signals were recorded bilaterally in the upper neck, trapezius, erector spinae, and external oblique, while kinematics were recorded with inertial sensors for the head, trunk, and pelvis. Seated postural reactions after repeated sideways perturbations with the head in a neutral position adapted with decreased EMG amplitudes in the upper neck, erector spinae, and external oblique, and decreased neck angle displacement. Muscle onset latencies were unaffected. With the head laterally flexed to the left, the EMG amplitude in the muscles on the right increased. The muscle onset latencies also started to adapt with increased muscle onset latencies at later repetitions when the head postures were flexed[15]. These findings suggest the advanced neuromuscular adaptation of *cephalic* vertebra for irregular external forces.

III. “Pelvic Vertebra”

In the 1970s, full spine X-rays including the pelvis and hip joints in a standing position became available in France, leading to many radiological studies on sagittal spinopelvic curvature. During a discussion on the issue, an important research question was raised to identify a pelvic parameter that would be key in describing the relationship between spinal curvature and pelvic morphology in the sagittal plane. One of the great achievements in this epoch was the discovery of a new pelvic parameter, the “angle of sacral incidence,” by Duval-Beaupère et al[16,17] which was later translated into pelvic incidence (PI) in English by Jean Legaye[18], a research fellow of Prof. Duval-Beaupère. PI represents the sum of the positional parameters: sacral slope and pelvic tilt. The term “angle of incidence” was used in analogy to geometric optics, where it describes the angle between a ray incident on a surface (mirror) and the line perpendicular to the

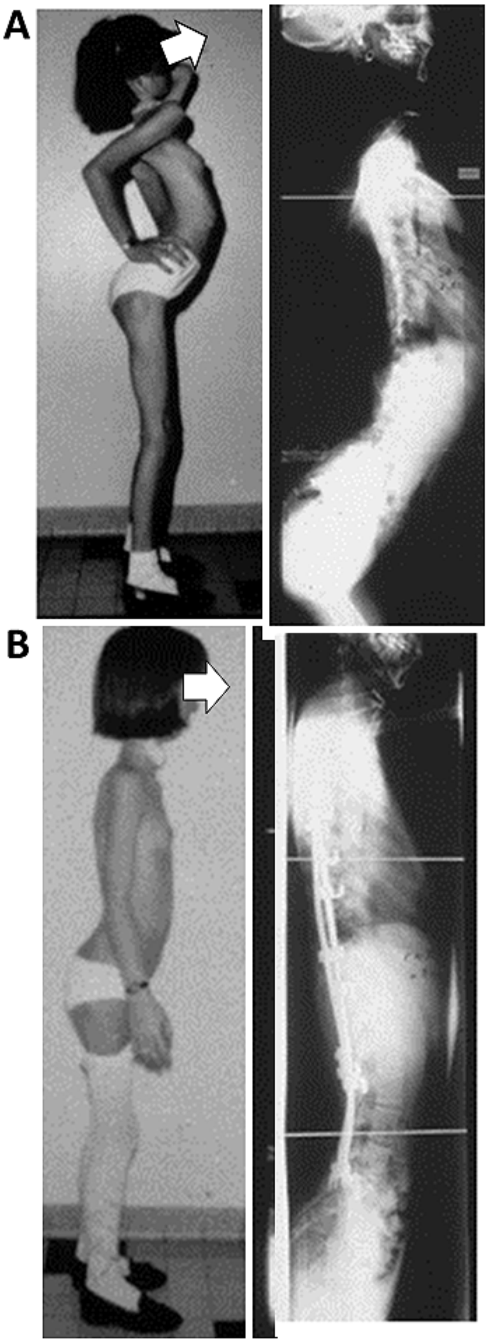

Figure 7. A 12-year-old girl with spinal lordotic deformity due to congenital muscular dystrophy. She always needed to hold the occiput by the hand in a standing posture before surgery (A), and she became stand naturally with horizontal gaze without hand help after spinopelvic correction surgery (B). Arrows represent the direction of the vision.

surface at the point of incidence. The incident ray originates from the center of the hip joints, whereas the mirror is represented by the sacral base. They showed that PI determines the amount of lumbar lordosis that provides the most economical upright posture in terms of muscle fatigue and vertebral strain for each individual at a given pelvic tilt, where the center of the sacral base is located more or less backward and upward in relation to the hip joints. The sagittal alignment with cervical lordosis, thoracic kyphosis, and lumbar lordosis is considered to be one of the most important evolutionary adaptations to bipedal locomotion, providing a good arrangement between mobility and stability. Tardieu et al. proposed that sagittal alignment and balance of the trunk on the hip joints are essential for the shift from an occasional to a permanent form of bipedalism, the significant hominid evolution, i.e., in the lineage leading to modern humans that includes all forms since the split from the chimpanzee lineage[19].

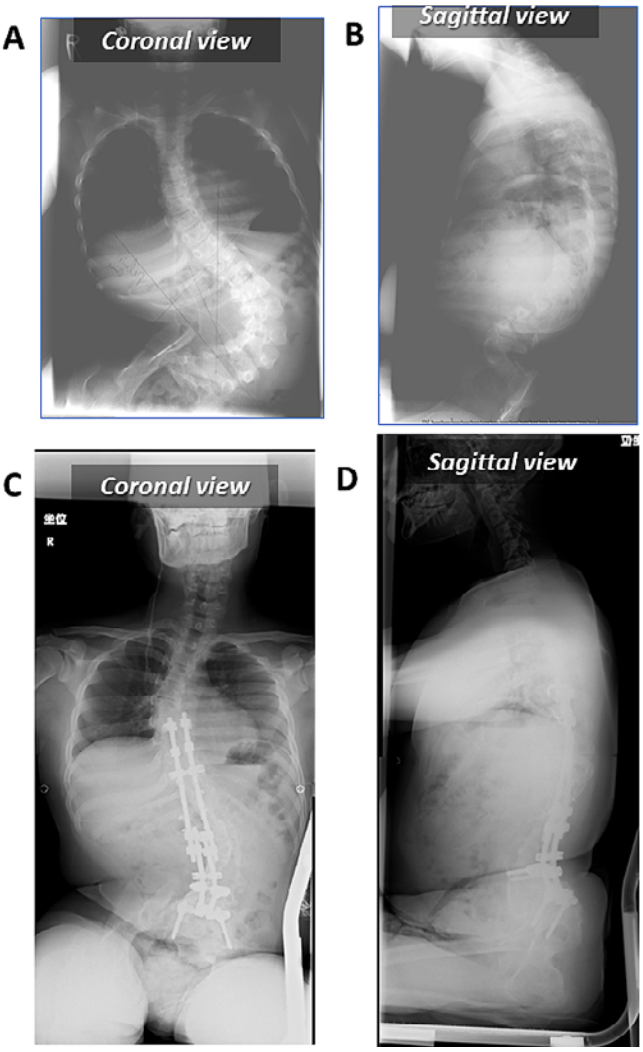

Figure 8. A 10-year-old boy, paralytic spinal deformity due to myelomeningocele. Before (A, B) and 20 years after surgery (C, D).

How does the pelvis work in a patient with complete paralysis of the trunk and lower limbs? A 10-year-old boy who suffered from paralytic spinal deformity with pelvic obliquity following surgical treatment for myelomeningocele was referred to us for treatment of the spinal deformity. He could not sit independently on a standard chair because of flaccid weakness of the trunk and lower limbs (complete paraplegia from the midthorasic level). X-rays showed severe lumbar kyphoscoliosis that included the pelvis (Fig. 8

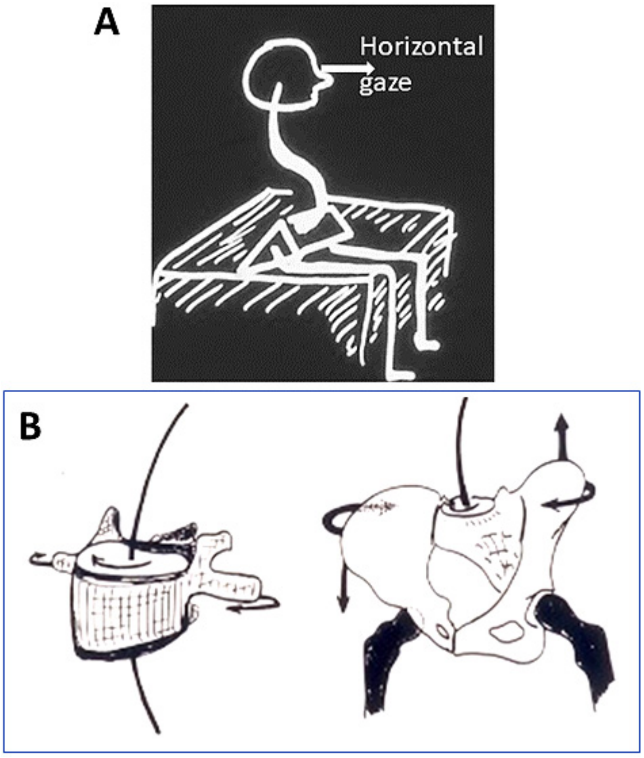

Figure 9. Stable spinopelvic alignment in the sitting position of a patient with complete paralysis of the lower limbs (A) and "pelvic vertebra" (B) drawn by JFD in 1972.

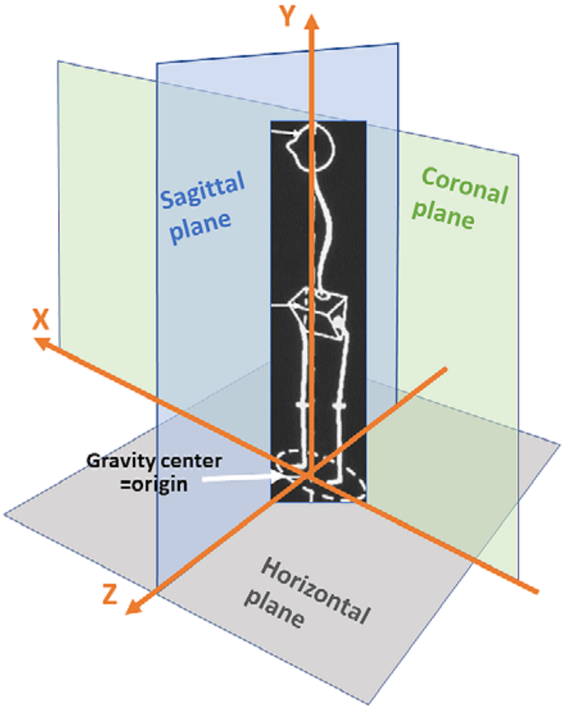

Figure 10. Reference planes and axes. Coronal plane coordinates are (X, Y), sagittal plane coordinates are (Z, Y), and horizontal plane coordinates are (X, Z). Gravity center is located at the origin of the three axes, and the gravity line corresponds with the Y axis.

A, B). Conservative treatment was ineffective, and we planned surgical treatment to obtain a stable sitting position. A correction and fusion surgery from T6 down to pelvis using a classical hybrid spinal system with hooks, pedicle screws, and iliac screws was performed. The 3D spinopelvic alignment was corrected and fusion was achieved. He was able to sit independently, and his daily activity using a wheelchair was remarkably improved. The coronal alignment was not perfect, but the 3D alignment and stability in the sitting position were maintained even 20 years after correction surgery (Fig. 8C, D).The purpose of the surgical treatment was to establish a stable sitting position with a horizontal gaze and to improve upper extremity function. This case demonstrates that correction and fusion surgery are effective not only in ambulant individuals but also in nonambulant individuals with paralysis. The key point for successful long-term results is the 3D spinopelvic realignment of the *chain of balance* from the cranium to the pelvis in this case (Fig. 8).

The pelvis makes it possible to be in balance during standing or sitting by intermediating the spine and lower limbs. The pelvis is therefore a key structure, especially for the upright posture in humans, the permanent bipedal mammals. Therefore, JFD termed the pelvis (intercalary bone) the "pelvic vertebra," in 1972, i.e., the pelvis is considered the most caudal vertebra of the spinal column (Fig. 9).

IV. Recent Evidence Supporting the Concept of the *Cone of Economy with the Chain of Balance*

The hypothetical concept of the *cone of economy* motivated us to launch a quantitative analysis of the alignment and balance of standing posture. First, when we analyze standing whole body alignment and balance, 3D coordinates are necessary. We built reference planes and axes in which the coronal plane coordinate is (X, Y), the sagittal plane coordinate is (Z, Y), and the horizontal plane is (X, Z). The gravity center is located at the origin of the three axes, and the gravity line corresponds to the Y axis (Fig. 10). The gravity line (GL) is the center of the "polygon of support" of the body and is more or less circular or ellipsoidal and represents the projection of the gravity line around both feet on the ground for the standing position or around both thighs and ischial tuberosities on the frame for the sitting position. The coordinates give us the basis to investigate the concept of the *cone of economy* where the body remains balanced within this surface with minimal muscle action in a normal situation[1].

In 2014, we established a whole body standing alignment measurement system with EOS and simultaneous GL captured by force plate measurement[20]. This system allows for accurate assessment in reference to the GL, the biomechanical datum line. We defined the GL as follows: tracking of the gravity center is recorded during EOS imaging in the horizontal plane with a force plate (ANIMA, Tokyo, Japan),

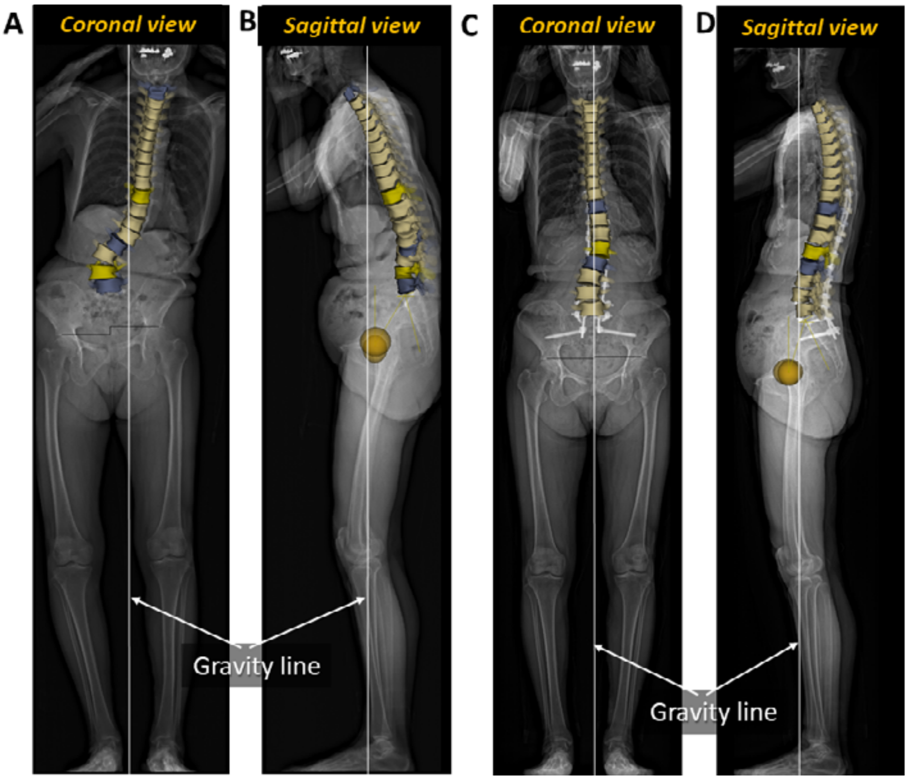

Figure 11. EOS images with the gravity line in the same case as shown in Figure 5. Before surgery: coronal view (A), sagittal view (B), and 2 years postoperatively: coronal view (C), sagittal view (D).

the mean location of the track for 30 s is defined as the mean gravity center, and the vertical line from the gravity center is defined as the GL. In the case shown in Fig. 5 before surgery, the relative location of the cephalic vertebra (cranium) is left anterolateral, the pelvic vertebra (pelvis) is right posterolateral, and the knee joints are flexed anterior to the GL, respectively (Fig. 11A, B). Following correction surgery, the components of the *chain of balance* are favorable relative to the GL, i.e., the center of the cranium is on the GL; cervical lordosis, thoracic kyphosis, lumbar lordosis with an L4 apex, and sacral base position are restored; hip axis is just anterior to the GL; and the center of knee joints and ankle joints are posterior to the GL in the sagittal plane (Fig. 11C, D)2). Therefore, with just a glance, we can easily determine whether or not the subject is balanced.

Recent progress in EOS using a new method with EOS-based virtual barycentremetry (avatar) permits estimation of the GL without force plate measurement. The procedure consists of three steps: 1) 3D reconstruction of the bone based on EOS images; 2) deformation into a generic morphotype (MakeHuman statistical model) with 3D rasterization of the full body into 1 mm^3 voxels; 3) computation of the density of all the voxels provides the center of mass, which can be projected onto the floor as the gravity center of the full body, providing the GL. The application of this method allows clinicians to quickly and qualitatively evaluate whole body alignment with the GL with various spinal malalignment pathologies21).

In the early 1980s, Graf et al., under the direction of JFD, performed 3D modeling of the vertebral alignment using computer analysis of coronal and sagittal X-ray films in 30 infantile scoliosis cases. They clearly described the possibility of 3D demonstration of the spinal column in coronal, sagittal, and even horizontal views8). The horizontal view, the top view, sheds light on the etiology of scoliosis curve progression22). The horizontal view is also valuable for estimating the compensation grade in patients with adult spinal deformity. The term decompensated means that the subject is unable to maintain a standing posture with a horizontal gaze and the orientation of the cranium is outside the normal range4,23,24). To determine the orientation of key axial bones, such as the cranium, vertebrae, sacrum, hip joints, knee joints, and ankle joints, we reconstructed a horizontal view using EOS 3D imaging and force plate measurements4). The locations of the gravity center and the center of each part of the body; center of the acoustic meati (CAM), thoracolumbar vertebrae, sacral base, bilateral hip joints, bilateral knee joints, and bilateral ankle joints in the case of Fig. 5 are shown in the horizontal plane before and after surgery (Fig. 12). Before surgery, the location of the CAM is more than 5 cm left anterolateral to the GL. The vertebrae and sacral base are distorted. The hip joints are right posterolaterally and the knee joints are right anterolaterally located to the GL before surgery (Fig. 12A, B). After correction surgery, the location of the CAM, all of the vertebrae, and sacral base are approximated to the GL. The location of the hip

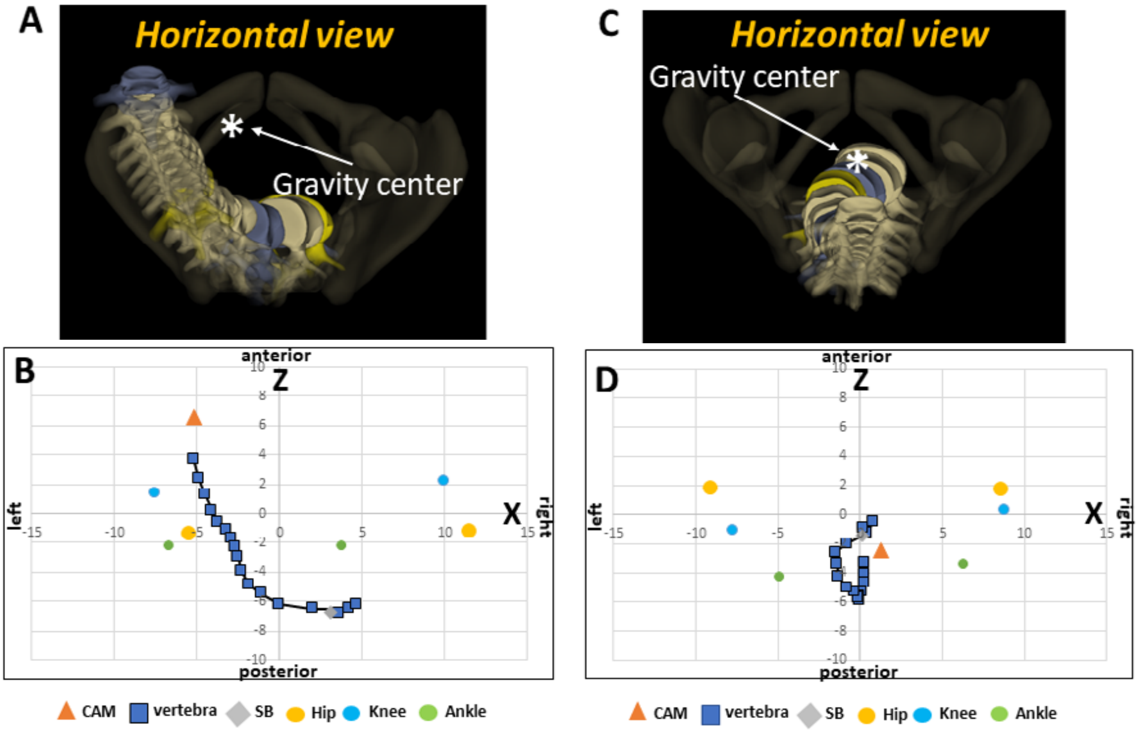

Figure 12. Evaluation in horizontal view of the same case as shown in Figure 5 using EOS 3D reconstruction images with gravity center and landmarks of the axial skeleton in X-Z coordinates before surgery (A, B) and 2 years postoperatively (C, D) in the same case as shown in Figure 5. CAM: center of acoustic meati, SB: center of the sacral base, Hip: center of hip joints, Knee: center of knee joints, Ankle: center of ankle joints

joints are anterior to the GL, and the knee joints and the ankle joints are posterior to the GL (Fig. 12C, D). The horizontal view shows a clear improvement of the whole body alignment to a more economic condition.

The locations of the center of the landmark bones in Fig. 12 are the mean locations of each gravity center sway in 30 s by force plate measurement. Here, we demonstrate the real movement of the gravity center in the horizontal plane coordinates. Before surgery, the sway of the gravity center was wide and rapid: the enveloped area of the track (ENV): 1.67 cm^2; total length of the track (TL): 37.32 cm; and speed of the track (speed): 1.24 cm/s (Fig. 13A). Following correction surgery, the sway became smaller and slower: approximated to the gravity center (the origin), ENV: 0.38 cm^2; TL: 25.31 cm; and speed: 0.84 cm/s (Fig. 13B), suggesting that the cone in the standing posture became smaller, i.e., more economic. Further analysis on the amplitude of the sway in the coronal and sagittal planes revealed that the sway was irregular and gradually increased with time both before and after surgery, but the increase was small in the postoperative standing posture (Fig. 13C, D). These findings imply that the body sway while standing, the movement of the cone, is not like a smooth top spinning, but is rather irregular with moment-by-moment adjustments of the position of the *chain of balance*. The increase in the sway amplitude is considered due to muscle fatigue, which is significantly greater before surgery than the postoperative condition.

In the standing posture, muscle activity in a patient with spinal deformity is considered to be greater than that in a subject without deformity. To verify the difference, we investigated the muscle activity using surface EMG in a 65-year-old woman with severe kyphosis before and after spinal correction surgery (Fig. 14). Integrated EMG (iEMG) [mV*sec] in 10 muscles, bilateral paraspinal muscles at the L5 vertebral level (PSM), biceps femoris (BF), rectus femoris (RF), gastrocnemius (GC), and tibialis anterior (TA) in the resting standing position was measured. The sums of the iEMGs before surgery was 13, 624 (PSM 631; BF 2321; RF 7184; GC 405; TA 3083) (Fig. 7A). Following correction surgery, the sum of the iEMGs significantly decreased to 6373 (PSM 1329; BF 1145; RF 2081; GC 1209; TA 609) 3 months after surgery (Fig. 7B) and 4841 (PSM 880; BF 844; RF 864; GC 1673; TA 580) 6 months after surgery. The difference in the muscle activity before and after surgery was noticeable with higher activity before surgery, i.e., a larger cone or noneconomic, and lower activity after correction surgery, i.e., a smaller cone or economic[25]. In the same way, Banno et al. investigated the muscle activities of the thoracic and lumbar erector spinae, external oblique, gluteus maximus, rectus femoris, and BF by recording the upright and anterior flexion positions using surface EMG preoperatively and 1 year postoperatively in 14 adult patients with deformity and eight age-matched controls. Patients with deformity required higher activity of the lower extremity and trunk muscles to maintain a standing position compared with age-matched controls, and the muscle activity of the lumbar erector spinae decreased after correction surgery. The findings are mostly compatible with our results[26].

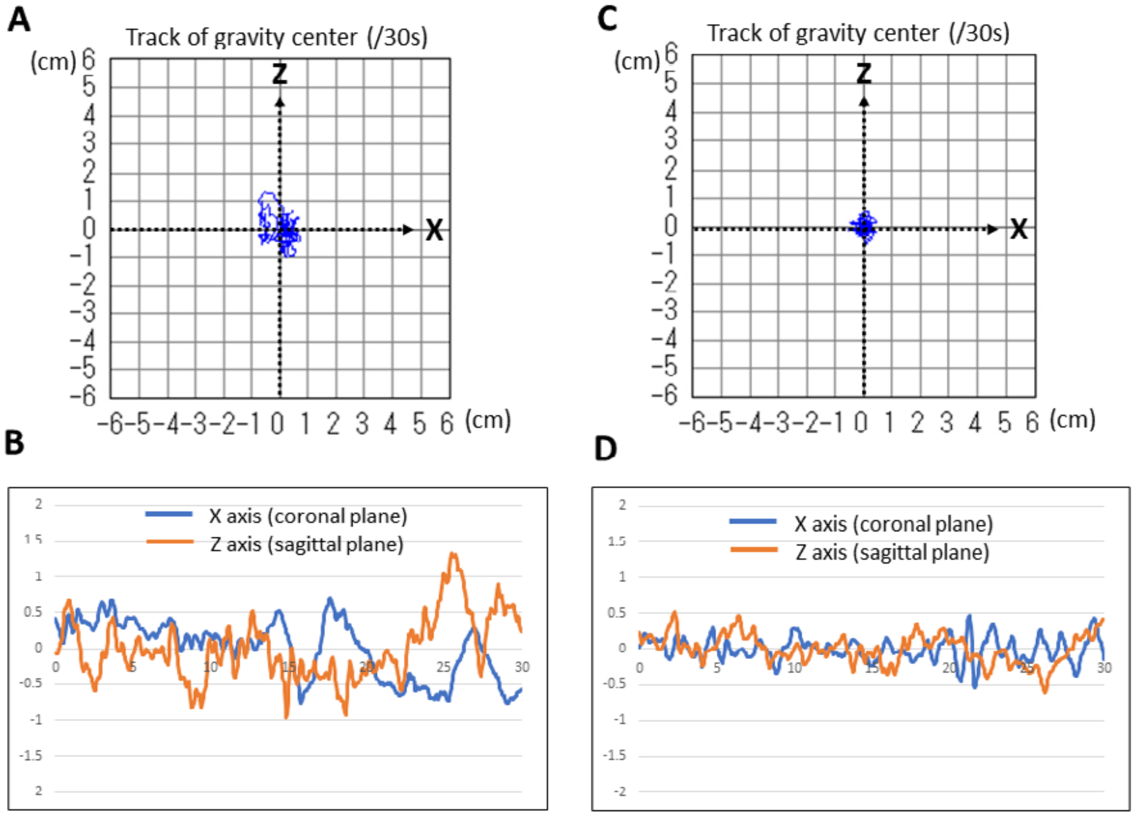

Figure 13. Evaluation by force plate measurement: Track of the gravity center in the horizontal plane for 30 s and the sway of the gravity center along the X axis (coronal plane) and Z axis (sagittal plane) in the same case as shown in Figure 5. Before surgery (A, B) and 2 years postoperatively (C, D).

Several investigations using modern methodology were recently launched. For example, Haddas et al. developed a measurement method for the *cone of economy* using a series of functional balance tests with a set of full-body reflective markers and surface electromyography in self-perceived balanced and a natural position for a full minute. They showed quantitative data of the boundaries of the *cone of economy* as the displacement of the center of mass and amount of sway within the cone, along with the energy expenditure for a specific patient[27].

The *cone of economy with the chain of balance* is a hypothesis based on JFD's clinical experience and deliberation. A great mathematician, Henri Poincaré stated that science is a hypothesis: Every generalization is a hypothesis; the hypothesis is a fundamental concept that should never be questioned but should be verified as soon and as frequently as possible through everyday clinical experience (translated by JFD)[28].

Conclusion

The bipedal erected posture with a horizontal gaze is a distinguishing feature of humans. Human locomotor function is complex. The standing mechanism is described as the concept of the *cone of economy* in which the axial skeleton aligns in balance from the feet, lower limbs, pelvis (*pelvic vertebra*), and spinal segments, ending with the cranium (*cephalic vertebra*). All the components act in concert, allowing for adaptive motion in all directions on the horizontal plane. Normal subjects can remain balanced within a small *cone of economy* with minimal muscle activity, whereas subjects with pathological lesions of the locomotor system require a larger *cone of economy* with greater muscle activity to maintain a standing posture. Recent studies have gradually consolidated the *cone of economy* concept, a fundamental hypothetical theory of human locomotion. We believe that further verification from various aspects will contribute to strengthening the validity of the concept.

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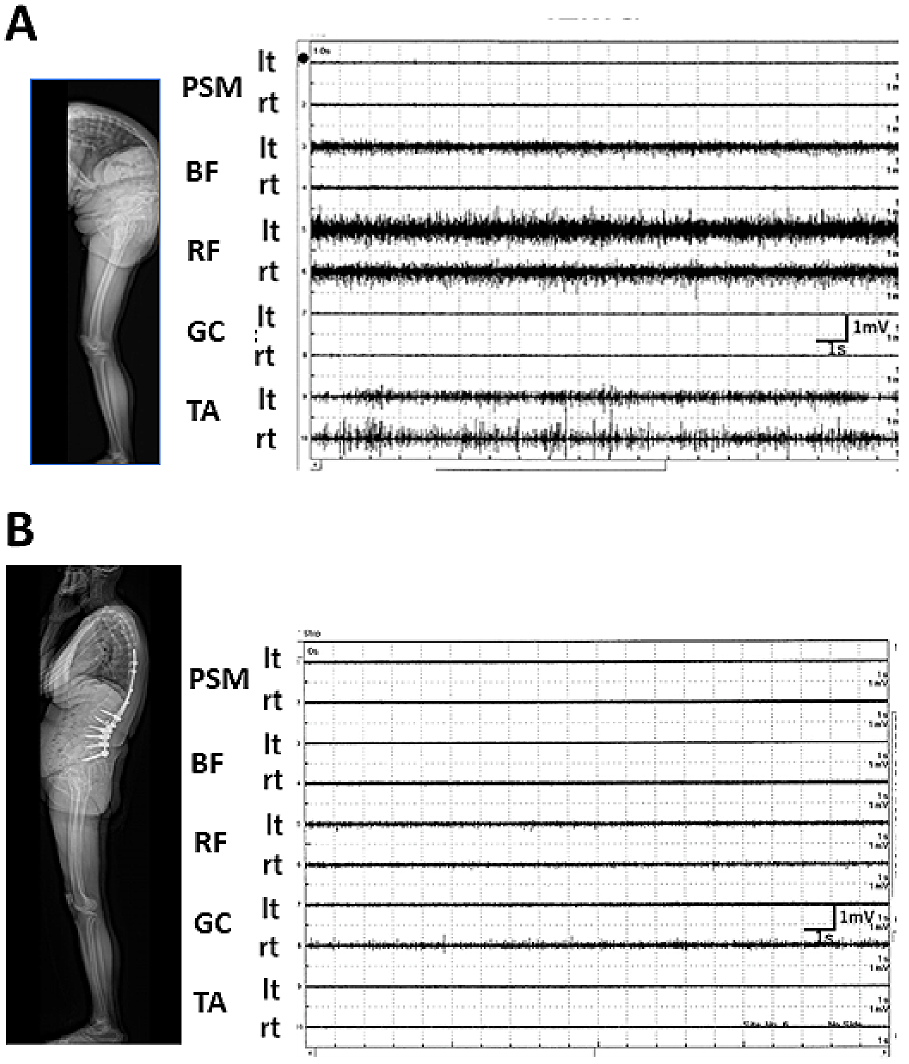

Figure 14. Comparison of integrated electromyogram (iEMG) between preoperative and postoperative (3 months) of a 65-year-old woman with severe degenerative kyphosis[25]. PVM: paravertebral muscle (m) (L5 level), BF: biceps femoris m, RF: rectus femoris m, Gastroc: gastrocnemius m, TA: tibialis anterior m, lt: left, rt: right

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