THE "PENDULUM LAW" – HOW TO EXPLAIN THE SPINAL SHAPE? PART I

A "LEI DO PÊNDULO" – COMO EXPLICAR A FORMA DA COLUNA? PARTE I

LA "LEY DEL PÉNDULO" – ¿CÓMO EXPLICAR LA FORMA DE LA COLUMNA? PARTE I

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ABSTRACT

The author uses the classical parameters that allow studying the sagittal form of the spine, following a vertebral semantics (lordosis, kyphosis, spinopelvic parameters, and sagittal balance). Then he proposes a very different perspective that analyzes the shape of the column, not in the sagittal-coronal plane but in the vertical plane, that is, integrating gravity as a three-dimensional construction axis. Beginning with an analysis of the global body scheme of which the column is part, the muscular synergies are introduced using reference points, defining tension lines, anatomical and functional arches, highlighting the importance of the respiratory function that stabilizes the shape of the thoracolumbar spine. This shows that, whatever the pelvic or frequent anomalies, the biomechanical scheme depends on a single unique law related to gravity: the "pendulum law". This allows us to define an ideal shaped spine, in comparison to different models, evoking the semantic practical and therapeutic interest of such a perspective.

Keywords: Spine; Postural balance; Spinal curvatures; Biomechanical phenomena.

RESUMO

O autor emprega os parâmetros clássicos que permitem estudar a forma sagital da coluna, seguindo a semântica vertebral (lordose, cifose, parâmetros espinopélvicos, equilíbrio sagital). A seguir, propõe uma perspectiva totalmente diferente que analisa a forma da coluna, não no plano sagital-coronal, mas sim no plano vertical, ou seja, integrando a gravidade como o eixo de construção tridimensional. Começando com uma análise do esquema global do corpo, do qual a coluna faz parte, as sinergias musculares são introduzidas usando pontos de referência, definindo linhas de tensão, arcos anatômicos e funcionais, enfatizando a importância da função respiratória que estabiliza a forma da coluna toracolombar. Isso mostra que, sejam quais forem as anomalias pélvicas ou frequentes, o esquema biomecânico depende de uma única lei relacionada com a gravidade: a "lei do pêndulo". Isso nos permite definir a forma ideal da coluna, em comparação com modelos distintos, evocando o interesse semântico prático e terapêutico desse tipo de perspectiva.

Descritores: Coluna vertebral; Equilíbrio postural; Curvaturas da coluna vertebral; Fenômenos biomecânicos.

RESUMEN

El autor utiliza los parámetros clásicos que permiten estudiar la forma sagital de la columna, siguiendo una semántica vertebral (lordosis, cifosis, parámetros espinopélvicos, balance sagital). Luego propone una perspectiva totalmente diferente que analiza la forma de la columna, no en el plan sagital-coronal sino que en el plan vertical, es decir, integrando la gravedad como eje de construcción tridimensional. Comenzando por un análisis del esquema corporal global del cual forma parte la columna, se introducen las sinergias musculares utilizando puntos de referencia, definiendo líneas de tensión, arcos anatómicos y funcionales, resaltando la importancia de la función respiratoria estabilizadora de la forma de la columna vertebral toracolumbar. Esto demuestra que, cualesquiera que sean las anomalías pélvicas o frecuentes, el esquema biomecánico depende de una única ley única vinculada a la gravedad: la "ley del péndulo". Esto permite definir una columna vertebral de referencia, en comparación a modelos distintos, evocando el interés semántico práctico y terapéutico de tal perspectiva.

Descriptores: Columna vertebral; Balance postural; Curvaturas de la columna vertebral; Fenómenos biomecánicos.

INTRODUCTION

Man is the only primate with a lumbar curve in lordosis. This ensures strictly vertical bipedal stability when walking.[1] The organization of sagittal curvatures, known since Hippocrates, is a succession of rigid kyphosis (sacrum, thoracic spine, cranium) and mobile lordosis (lumbar and cervical spines).

Most authors only analyze the thoracolumbar spine separately in the sagittal plane, using angular vertebral semantics to explain the shape and biomechanics of the spine. Commonly accepted conclusions found in the literature include:

There is a strong relationship between the slope of the sacrum and lumbar lordosis.[2]

Roussuly et al.[1,3,4] define different parameters that enable the sagittal study of the shape.

Spino-pelvic parameters (Pelvic incidence, sacral slope, and pelvic tilt).

Segmentation of the sagittal curves according to the point of inflection separating lordosis and kyphosis is proposed in order to obtain angular calculations. However, these points of inflection are variable.

Lumbar lordosis is thus divided into two parts by the lumbar apex:

A lower lordosis is closely associated with the sacral slope and an almost constantly higher lordosis (20°).

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- Finally, a classification of the sagittal shapes into four groups is proposed, according to the inclination and the slope of the sacrum.
- Sagittal balance is defined in terms of the vertebral body of C7 and seems relatively stable,[5] referring to either the sacrum or the center of the hips.
- The interdependence of the curvatures and the position of the pelvis are accepted by most authors.
- Statistical studies have analyzed these parameters in a large European population.[6]

However, all stress the great variability in these angulation calculations[7] that prohibits the defining of standards for them.[2] None actually proposes a scheme relating the curvatures to each other.

In this first part, we propose an overall biomechanical scheme that lets us define the ideal spinal shape in relation to two opposing models. In the second part, we explain the variations in the biomechanical scheme of the spine in terms of the anomalies commonly observed in patients with low back pain. This different view is based on a functional analysis of the corporal scheme (which includes the spine) in the vertical plane. In other words, it only refers to gravity as the axis of 3D construction. It is these rules that we will discuss here and that we will call the “Pendulum Law”.

MATERIALS AND METHODS

The analysis of the difference between the pre- and postoperative total column radiographies of 300 patients who underwent standalone ALIF, in addition to several patients received daily for consultations about chronic low back pain, enabled us to establish the rules of the biomechanical scheme of the body proposed below.

Construction of the spine in the vertical plane

During growth, the spine acquires its shape against gravity. The muscle-aponeurotic synergies have the function of maintaining the vertical spinal anatomy in the three spatial planes (sagittal, coronal, and rotational). They integrate the current anomalies and organize the corporal biomechanical scheme, of which the spine is a part, as a function of this constant gravitational rule. (Figure 1)

We will define various important points; whether they are points of contact of the vertical with the curvatures (apex) or because they have a relationship with the anatomy (point of inflection of the curvatures, lung), or symbolize the muscle-aponeurotic complex insertion (reflection pulley, point of insertion).

The relationship between these points define the lines of tension of the three anatomical and/or functional arches, (Figure 2) permitting the establishment of a corporal organization scheme:

- Ensure the vital respiratory function, ensuring the equilibrium of lung pressures at a lower energy cost.
- Ensure the independence of breathing as a function of locomotion, as well as the stability and movement of the head via mobile “shock absorber” curvatures (Lumbar and cervical lordosis).
- The functional scheme of the thoraco-lumbar spine (which is the essential vertical axis of the corporal scheme) is consequently dependent on the respiratory function and its corporal muscular involvement.

Definition of the “Pendulum law” in the frontal plane

We found that whatever the “common” structure of an adult’s spine, the only points of reference between them are that the pulmonary apices are horizontal and that their purpose is to balance the pulmonary pressures in breathing (pneumatic stabilization). The muscle synergies of the corporal scheme are asymmetrical. The point of attachment (A) of the pendulum is defined as the midpoint between the two pulmonary apices.

The plumb line remains above the sacral apex (point S). The point of confluence of the muscle-aponeurotic extensor complex is in front of point S.

The movement of the pendulum remains vertical (trunk) despite the oscillatory movements of the pelvis, the rotational axis of which is point S. When the trunk is in motion, the pendulum materialized from point E (equilibrium of muscle synergies) returns to its resting position. The height of the point (E) depends on the sagittal shape. The shape appears as a transient state in which the opposing forces are canceled around the vertical axis of the pendulum (Figure 3).

In most cases, existing vertebral (rotatory and/or sagittal) or pelvic (sacral inclination) anomalies and degenerative changes have little impact on this “rule”, which is challenged by more serious out-of-the-ordinary rotatory anomalies. We can then speak of pneumatic stabilization as logic for vertical construction of the thoracolumbar spine and the corporal scheme

In the sagittal plane (Figure 4)

There are two imperatives:

Stabilize the foundation (the pelvis) upon which the corporal construction is built.

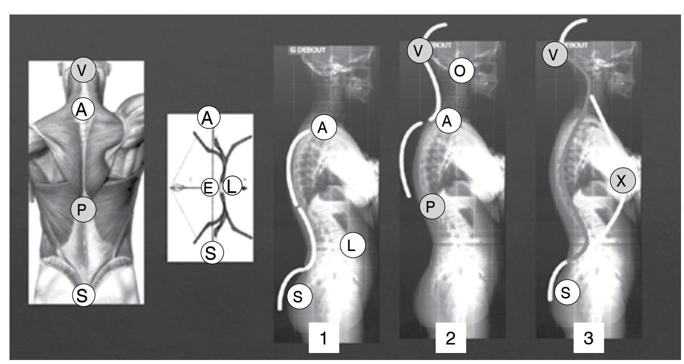

Figure 2. The three interwoven functional arches.
(A) point of attachment, (P) Lower posterior-inferior pulmonary apex, (S) sacral apex, (E) Equilibrium of muscle synergies, (L) lumbar apex, (O) occipital-cervical joint, (X) lower anterior pulmonary apex.

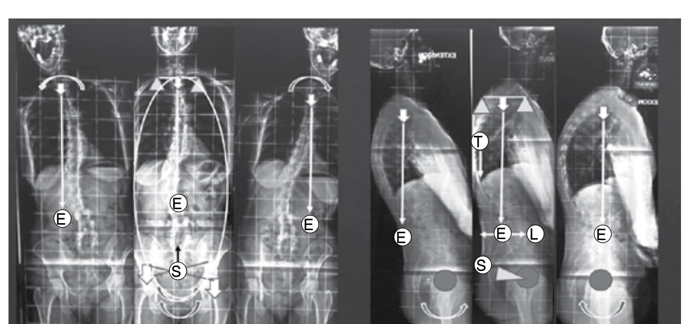

Figure 3. The shape depends on the stabilization of the pendulum.
(E) Equilibrium of muscle synergies; (S) sacral apex, (T) Thoracic apex, (L) lumbar apex.

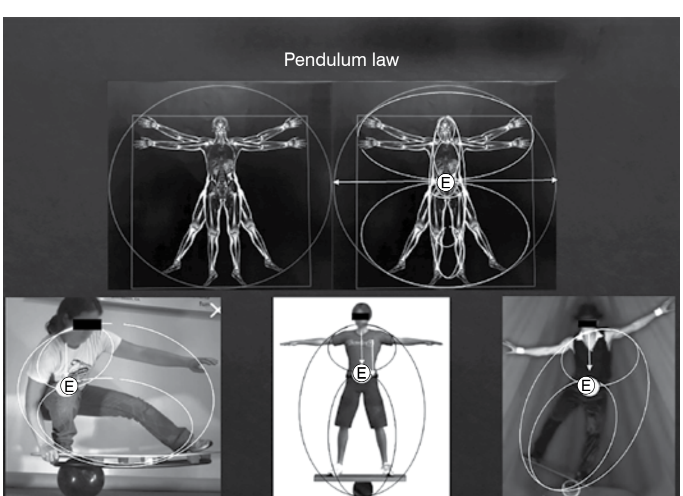

Figure 1. Relationship between the body and gravity.
(E) - Equilibrium of muscle synergies.

The line that connects the apex of the sacrum (S), the center of the femoral heads (F), and the pubic symphysis (Y) constitutes the pelvic base in motion around (F) but stabilized by the antagonistic synergies of the muscles (glutei, psoas, abductors) of the lower limbs.

Whatever the "common" sagittal forms of the subjacent spine, the angle between the S/F segment and the horizontal plane is considerably fixed. Defining the "angle of stabilization of the base", its value is 15° (+/- 4°). The S/F distance is the "lever arm". It lengthens when the pendulum moves forward and shortens when it moves back.

Suspend the pendulum, the upper connection of which is the pulmonary apex (A), accurately.

Equilibrium of the pulmonary pressures is by needs applied in the sagittal plane during breathing. The pendulum always has point A as its connection. Normal breathing does not affect the pendulum or the sagittal position of the spine. Deep inhaling and exhaling and flexion-extension movements make the pendulum move. The resting point (E) of the pendulum lies equidistantly between the anatomical lumbar apex (L) and the vertical of the anatomical thoracic apex (T). It is located at the intersection of the vertical line from point A and the horizontal line passing through the anatomical lumbar apex (L), and is the point of equilibrium of the muscle synergies, defining the functional lumbar apex. The E/L distance is the arrow.

By definition then, the pendulum depends on gravity. It defines a "vertical line of tension" in the corporal muscle scheme: the A/E distance. Its position in space in relation to the base depends on changes and existing anatomical anomalies, but it remains the generator of the corporal biomechanical scheme, as a result of the spine.

Definition of the ideal spine (Figure 4)

The corporal scheme (that of the spine) will be defined by its anatomical and functional apices, which are at the same time pulleys of reflection of aponeurotic and muscular tensions and/or points of inflection of the curvatures. Therefore, its development follows the muscle synergies and depends on respiratory function.

Ideally, it is organized according to two schemes:

A vertical anatomical construction

That aligns the thoracic apex (T) above the sacral apex (S) (seeking verticality), creating an ideal lordosis aligning the thoracic apex (T), lumbar apex (L), and the symphysis (Y) within the axis of traction of the psoas. This line crosses the vertebral bodies harmoniously and obliquely. It defines an anatomical triangle connecting the angles (S, Y, T) stabilized above the center of rotation (F). The projection of L results from the plumb of F. The lumbar apex (L) is located in front of the upper plateau of L4.

A functional construction

The spine is made up of a series of rigid/flexible anatomical arches: sacral (rigid arch), lumbar (flexible), thorax (rigid), cervical (flexible), cranial (rigid), constituting a double reverse S system that ensures the Independence of the respiratory function.

With locomotor apparatus (sacral/lumbar/thoracic arch).

With movements of the head to the other side (thoracic/cervical/cranial arch).

The major line of the "tension of the functional arches" in this "ideal form" connects the apex of the sacrum (S), the posterior-inferior pulmonary apex (P), the superior pulmonary apex (A), the occipital-cervical joint (O), and the cranial apex (H).

The arrows are perpendicular to this line, distributed on either side of it, joining the points farthest from the curvatures. They are parallel and practically equidistant from its point of inflection. (Figure 5)

The shape and position of the thorax are defined as a function of its apices (A, X, P). The lower anterior pulmonary apex (X) defines the lower arrow of the thorax. The point P is the lower posterior pulmonary apex.

It represents the functional thoracic apex.

The thorax is intimately dependent on the "pendulum" and by consequence on the lumbar apex. Regardless of the existing anomalies, the lines of pelvic thoracic tension X/S and P/S always intersect at E.

The occipital cervical joint, when at rest, is located in a position within the prolongation of the rigid thoracic arch (P/A). The point of rotation of this P/A/O segment is A. It defines the line of tension of the thoracic cervical arch.

This system is called "ideal" since it aligns the two lines of tension of the functional pelvic thoracic (S/P/A) and thoraco-cervical (P/A/O) arches.

There is then a distribution of the anatomical/functional apices in the space that defines a shape and an "ideal" biomechanical scheme that will serve as a reference.

The variations of the sagittal shapes (Figure 6)

They depend solely on the integration of the isolated or associated anomalies (to be studied in the second part) by gravity. Here we will present two opposing models and compare them to the ideal scheme.

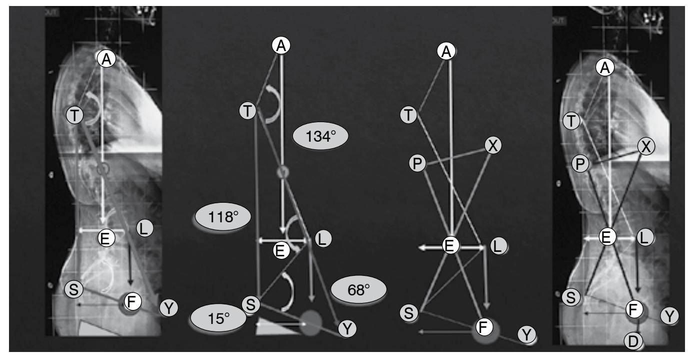

Figure 4. The criteria for an ideal spine.
(A) Point of attachment, (E) Equilibrium of muscle synergies, (F) Femoral heads, (L) lumbar apex, (P) Lower posterior-inferior pulmonary apex, (S) sacral apex, (T) Thoracic apex, (X) lower anterior pulmonary apex, (Y) Symphysis.

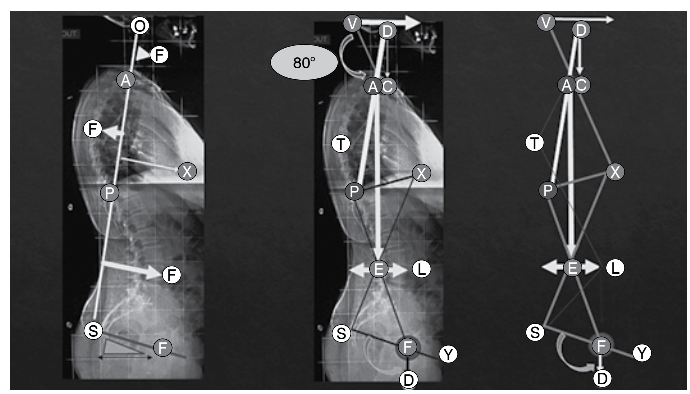

Figure 5. Ideal biomechanics: equidistant arrows.
(A) Point of attachment, (E) Equilibrium of muscle synergies, (F) Femoral heads, (L) lumbar apex, (P) Lower posterior-inferior pulmonary apex, (S) sacral apex, (T) Thoracic apex (X) lower anterior pulmonary apex, (Y) Symphysis.

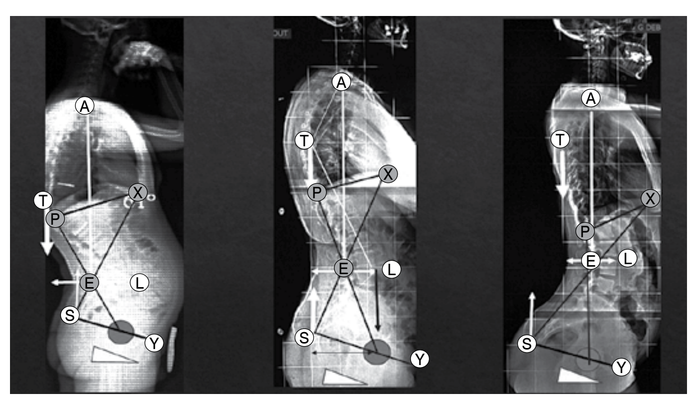

Figure 6. Opposing models comply with the pendulum law.
(A) Point of attachment, (E) Equilibrium of muscle synergies, (L) lumbar apex, (P) Lower posterior-inferior pulmonary apex, (S) sacral apex, (T) Thoracic apex (X) lower anterior pulmonary apex, (Y) Symphysis.

The anomalies modify the distribution of the apices. The modified anatomical triangle is relocated in the center F to compensate for the horizontal displacement and the height of the pendulum and to maintain the angle of stabilization. However, the law continues to suspend (attach) the pendulum in such a way that it is equidistant from the lumbar and thoracic apices. Therefore, the pendulum organizes the biomechanical scheme.

The alignment of T with S slides forwards or backwards according to the anomalies.

There is a disassociation of the lines of tension of the functional arches P/A/O whose axis is A (hook of the pendulum). Rotation depends on the height of the thoracic apex.

The position of the head (O) depends on this thoraco-occipital line P/A/O and also on the anterior line X/V. V represents the muscular insertion. The horizontal arrow passing through V is aligned with the vestibular duct/eyeball which enables the stability of the head when breathing. The line X/V passes through the cervical pendulum P and is intersected by the plumb line from O and the horizontal passing through A.

Overall, the corporal scheme depends on the relationship between the pendulum (line A/E) and the hips F, whatever the common anomalies. This scheme of proportionality linked to gravity demonstrates the independence of the interdependance of the curves.

DISCUSSION

The classifications of the shapes of the spine in the sagittal or coronal plane are based on angle measurements.

This type of analysis is static, mono-planar, and unsatisfactory.

The angle measurements vary depending on the patient's breathing or on whether or not the patient is in a relaxed position.

There are several shapes, including opposites, for the same angle (of lordosis or kyphosis or spino-pelvic parameters).

Pelvic incidence does not integrate the apex of the sacrum, which is the pulley of the extensor system whose axis is the hip. This mathematical construction (perpendicular to the medial part of the sacrum) does not account for the roll up of the sacrum or its vertical or sagittal anomalies. Furthermore, lumbosacral anomalies are quite common, relativizing interest in the slope of the sacrum in practice.

By isolating the thoracolumbar spine from the corporal scheme, the muscular synergies, including the stabilizing effect of breathing, and the notion of "de-alignment" of the T/S apices, which allow us to define specific biomechanics, are unknown. Lordosis does not depend on pelvic incidence except as a way to stabilize the thorax.

Gravity is the only axis of 3D construction, explaining the shape as a whole through a proportionality scheme. The lines of tension imply that the anomalies of the base (pelvis) and/or the spine are always interdependent. These modifications are organized around the pendulum law. An early and perfect surgical correction (Figure 7) of a major anomaly results in an adaptation in accordance with the standard scheme years later.

This law has multiple interests:

To explain and classify the patterns of degenerative discogenic collapse in the rotatory plane (de novo adult scoliosis) and in the sagittal plane.[8,9]

To analyze the modifications of the degenerative biomechanical scheme pre- and postoperatively in patients who undergo standalone ALIF. ALIF restores disc height and "re-extends" the anterior lumbar arch. The preserved muscles facilitate "auto-adaptation". The patient recovers and their biomechanical scheme improves according to the criteria of the Pendulum Law (Figures 8 and 9). This analysis gives us a more dynamic vision of the corporal scheme in its entirety and of the compensatory mechanisms that ensure our relationship with gravity (hip/head).

The therapeutic consequences are reduced iatrogenic costs associated with the use of posterior instrumentation in elderly patients.

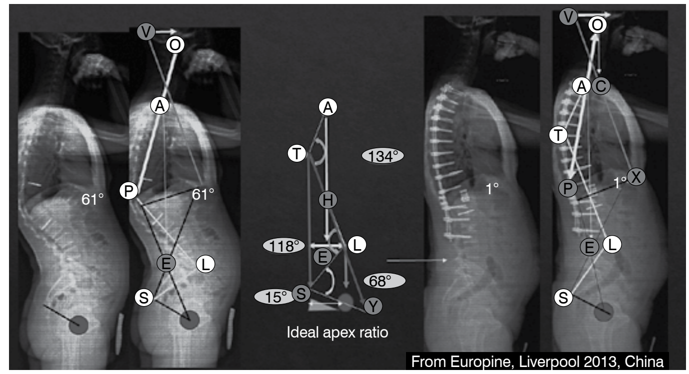

Figure 7. Auto-stabilization according to the ideal criteria.
(A) Point of attachment, (E) Equilibrium of muscle synergies, (L) lumbar apex, (O) occipital-cervical joint, (P) Lower posterior-inferior pulmonary apex, (S) sacral apex, (T) Thoracic apex (X) lower anterior pulmonary apex, (Y) Symphysis.

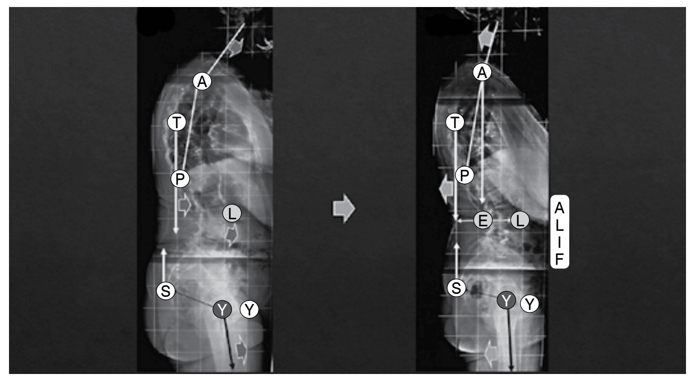

Figure 8. Analysis of the body before and after standalone A/OLIF.
(A) Point of attachment, (E) Equilibrium of muscle synergies, (L) lumbar apex, joint, (P) Lower posterior-inferior pulmonary apex, (S) sacral apex, (T) Thoracic apex (X) lower anterior pulmonary apex, (Y) Symphysis.

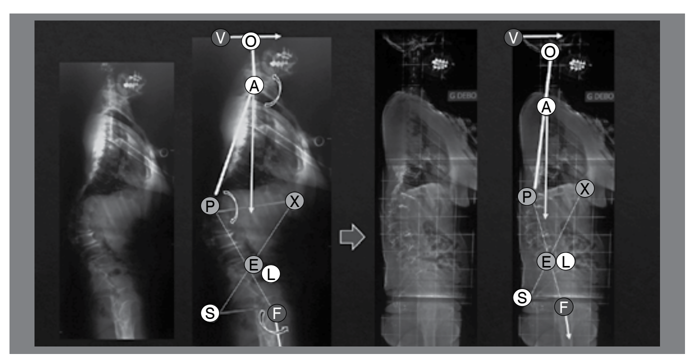

Figure 9. The patient recovers the shape of the spine according to the pendulum law.
(A) Point of attachment, (E) Equilibrium of muscle synergies, (F) Femoral heads, (L) lumbar apex, joint, (P) Lower posterior-inferior pulmonary apex, (S) sacral apex, (T) Thoracic apex (X) lower anterior pulmonary apex, (Y) Symphysis.

CONCLUSIONS

There will always be two complementary ways of thinking about the spine according to the pathology. Each of them has its own tools:

Bone semantics, centered on deformity, using angle measurements, sagittal analysis, imposing a definitive shape with posterior instrumentation.

Discogenic semantics, centered on the degenerative biomechanism (discogenic collapse), with classification of the degenerative collapses, and using standalone ALIF to preserve the muscles and improve the biomechanical scheme of the patient.

However, there is a single rule that explains three-dimensional nature of the spine: gravity. Therefore, we can propose a dynamic definition of the spine: "The shape of the spine appears as a transitory state in which the opposing forces cancel each other out around a vertical axis, stabilizing the pulmonary apices according to the criteria of the Pendulum Law so that the respiratory cost will be minimal".

This law has several interests:

To identify and classify the biomechanical schemes according to the anomalies. (PART II)

To study their specific degenerative biomechanisms.

To specify the indications and outcomes of standalone ALIF in degenerative pathology.

All the authors declare that there are no potential conflicts of interest regarding this article.

CONTRIBUTIONS OF THE AUTHORS: The author of this manuscript that describes an institutional study is GN.

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