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ORIGINAL ARTICLE

Compensatory mechanisms contributing to keep the sagittal balance of the spine

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Abstract
Introduction Aging spine is characterized by facet joints arthritis, degenerative disc disease, bone remodeling and atrophy of extensor muscles resulting in a progressive kyphosis of the lumbar spine.
Objective The aim of this paper is to describe the different compensatory mechanisms for patients with severe degenerative lumbar spine.
Material and methods According to the severity of the imbalance, three stages are observed: balanced, balanced with compensatory mechanisms and imbalanced. For the two last stages, the compensatory mechanisms permit to limit the consequences of loss of lumbar lordosis on global sagittal alignment and therefore contribute to keep the sagittal balance of the spine.
Results The basic concept is to extend adjacent segments of the kyphotic spine allowing for compensation of the sagittal unbalance but potentially inducing adverse effects.
Conclusion Finally, we propose a three-step algorithm to analyze the global balance status and take into consideration the presence of the compensatory mechanisms in the spinal, pelvic and lower limb areas.

Keywords Sagittal balance · Pelvis · Spinal alignment · Lumbar lordosis · Degenerative disc disease · Lumbar kyphosis

Abbreviations
LL Lumbar lordosis
PI Pelvic incidence
PT Pelvic tilt
SS Sacral slope
TK Thoracic kyphosis

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Introduction

Recent studies support the idea that analysis of sagittal balance is a crucial keypoint to optimize the management of lumbar degenerative diseases, especially when spinal instrumentation is intended [7, 13, 15, 16].

Aging of the spine is characterized by hypertrophic facet joints arthritis, degenerative disc disease, bone remodeling and atrophy of extensor muscles resulting in a progressive kyphosis of the lumbar spine with the risk to progressively develop a global sagittal unbalance [6, 10]. Similarly, patients with chronic low back pain and lumbar degenerative disease present with modifications of sagittal balance and are characterized by anterior sagittal imbalance, loss of lumbar lordosis, and increase of pelvis tilt [1, 2, 8, 9]. The anterior imbalance in patients' population is mainly due to the loss of lumbar lordosis even if the part of the structural loss of lordosis and postural part may be difficult to differentiate. Except the loss of lordosis, which is related to the degenerative process, the other changes in spino-pelvic parameters (for example decrease of sacral slope, reduction of thoracic kyphosis or increase of lordosis in upper lumbar spine) correspond to compensatory mechanisms. To optimize the management of lumbar degenerative disorders and avoid underestimation of the severity of the degenerative disease, it seems important to recognize and take into consideration these different mechanisms.

In the normal population, correlations between the pelvic incidence (which is a morphological parameter, pelvis shape related), the sacral slope and sagittal curves (especially lumbar lordosis) have now been well documented [3–6, 9, 20, 23, 25]. Consequently, it is now much easier to understand the changes of spino-pelvic parameters for patients with spinal degenerative disorders. The compensatory mechanisms contribute to keep the sagittal balance of the spine above the pelvis, thus limiting the consequences of lumbar kyphosis in terms of sagittal anterior imbalance. They are observed in the spine, pelvis and/or lower limb areas and can be associated [15].

The objective of this paper is thus to describe in detail these different compensatory mechanisms in patients with severe degenerative spine and sagittal balance disorders.

Global balance evaluation

Into the normal population a standard sagittal balance does not exist. It is essential to have an optimal congruence between pelvic and spinal parameters to achieve an economic posture placing the axis of gravity in a physiologic position [3, 5, 14, 17].

In the case of degenerative deformities of the spine, one of the most important step is to evaluate the global balance of the patient. This can be done optimally using strength plate and measuring positioning of the gravity axis in the sagittal plane [25]. However, in clinical practise, global balance is appreciated more simply by describing the relative positioning of the spine in reference with the pelvis on standing full spine radiographs. Global sagittal alignment is typically determined by calculating the offset between the posterior corner of the sacrum and the vertical line passing through the vertebral body of C7 (i.e. sagittal vertical axis, SVA). Instead of measuring a linear distance, we recommend to use angular and/or ratio parameters to characterize the positioning of C7 in relation to the sacrum. Angular parameter is represented by the spino-sacral angle (SSA) and the ratio corresponds to the C7 plumbline/sacro-femoral distance ratio (C7/SFD). These two parameters have already been reported and validated [1, 21].

The SSA was defined as the angle between the sacral plate and the line connecting the centroid of C7 vertebral body and the midpoint of the sacral plate (Fig. 1a). In the normal population the mean value of this angle is 135° ± 8 [21].

The method to measure C7/SFD ratio is presented in (Fig. 1b). This ratio is equal to zero, when C7 plumbline projects exactly on the posterior corner of the sacrum, and equal to one, when C7 plumbline projects exactly on the bicoxo-femoral axis. It is negative when C7 plumbline projects posteriorly to the sacrum, and more than one when C7 plumbline projects from anterior to the femoral heads. In the normal population the mean value of this ratio is −0.9 ± 1 [1].

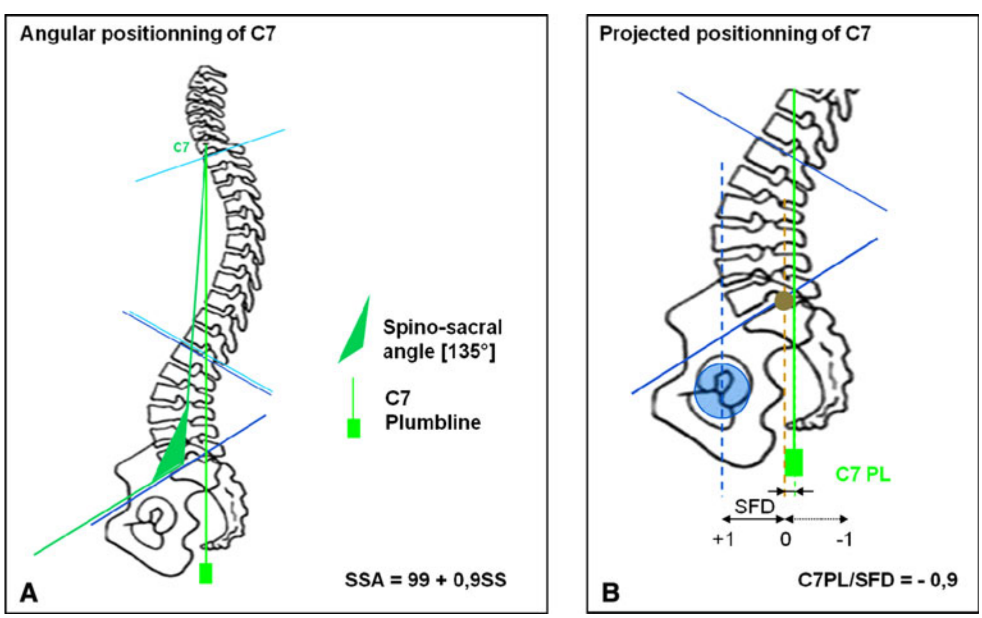

Fig. 1 Evaluation of global sagittal alignment using the spino-sacral angle (**a**) and the C7/SFD ratio (**b**). The SSA is defined as the angle between the sacral plate and the line connecting the centroid of C7 vertebral body and the midpoint of the sacral plate [23]. Sacro-femoral distance (SFD) is the horizontal distance between the vertical bicoxo-femoral axis and the vertical line passing through the posterior corner of the sacrum. The horizontal distance between C7 PL and the posterior corner of the sacrum (that is SC7 D) was also measured. Then we calculated the C7/SFD ratio corresponding to the ratio between SC7 distance and SF distance [1]

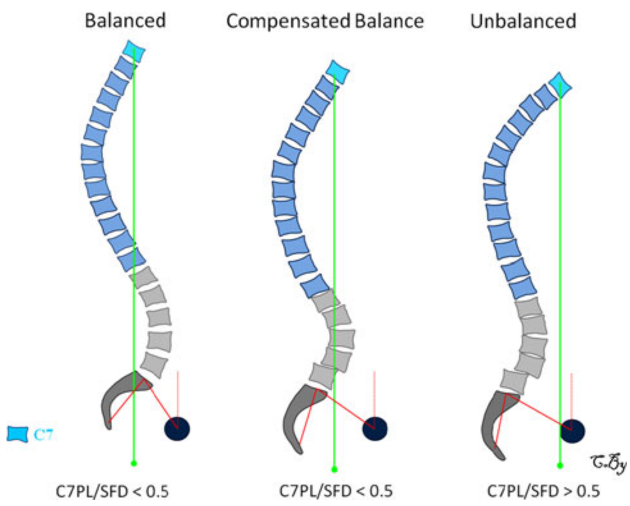

Fig. 2 Classification of global sagittal alignment in three stages with respect to the severity of the imbalance. In stage 3 (*unbalanced*) C7PL/SFD ratio is superior to 0.5 signifying that C7 plumbline lies closer to femoral heads than to sacral plate

The spino-sacral angle and the C7/SFD ratio permit to evaluate the global sagittal alignment of the spine above the pelvis. According to the severity of the imbalance, we propose to identify three different stages: balanced, balanced with compensatory mechanisms and imbalanced (Fig. 2). In the last stage, the compensatory mechanisms are not enough efficient to maintain the sagittal balance.

Compensatory mechanisms

Compensatory mechanisms are observed in the spine, the pelvis and/or the lower limb areas and are summarized and illustrated in Fig. 3. Although these mechanisms are rarely observed all together in the same patient, they are usually associated at different degrees, depending mainly on the stiffness of the spine, the musculature status, painful phenomena and the severity of the unbalance.

Their basic concept is to extend adjacent segments of the kyphotic spine allowing for compensation of anterior translation of the axis of gravity but potentially resulting in adverse effects.

To understand the variations of positional parameters such as SS, PT, LL and TK in the patients' population, we previously published values of six different classes of pelvic incidence in a normal control group of 154 subjects [2]. Values of positional parameters for each class of PI (from I to VI corresponding to a progressive increase of the PI value) are summarized in Table 1. Theoretical normal values for spino-pelvic parameters can also be estimated from mathematical relations (Table 2). Otherwise, to analyze segmental changes, we have to keep in mind that the L4–S1 segment provides the 2/3 of the total lumbar lordosis [9, 11, 20].

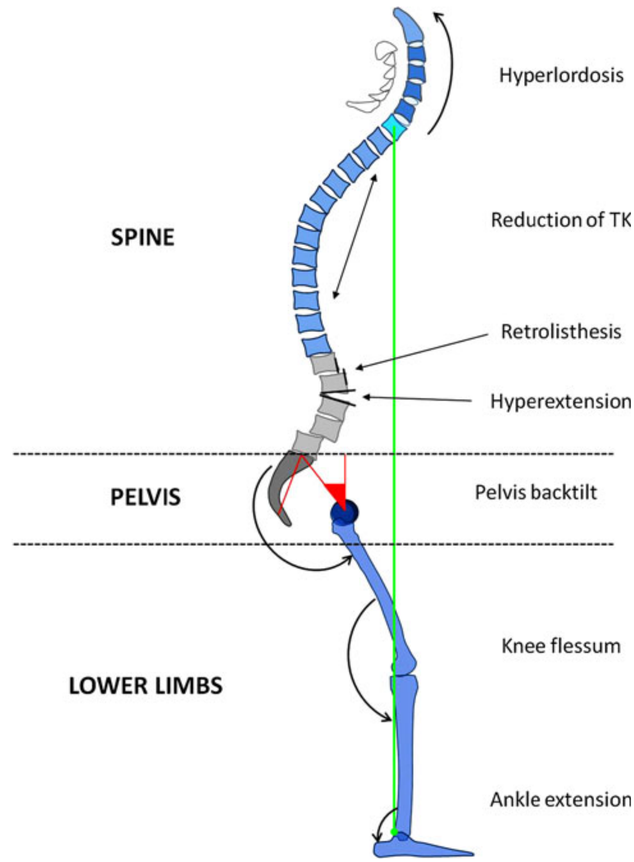

Fig. 3 Sagittal imbalance and the different compensatory mechanisms in the spine, pelvis and lower limb areas

Spine area

Cervical hyperlordosis

Although in most cases the cervical spine is not well evaluated on full spine radiographs, it should be included in the sagittal balance assessment since compensatory curvature can be observed at this level. Hyperextension of the cervical spine is a typical compensatory mechanism above a thoracic hyperkyphosis to maintain the horizontality of the gaze. Inconveniences related to this hyperlordosis are not negligible corresponding to acceleration of degenerative changes in the cervical spine (i.e. hypertrophic facet joints arthritis), presence of axial neck pain, foraminal stenosis and the risk to develop spondylotic myelopathy.

Reduction of thoracic kyphosis

Reduction of thoracic kyphosis permits to limit anterior translation of the axis of gravity and is typically observed in young patients with flexible spine (Fig. 4). Takemitsu et al. [24] described this mechanism for patients with

Table 1 Classes of pelvic incidence and corresponding values of spino-pelvic positional parameters from a group control of 154 subjects [2]

	n	PI	PT	SS	LL	TK
I	12	35.4 ± 1.3	3.9 ± 4.5	31.5 ± 5.2	53.3 ± 6.6	43.8 ± 9.1
28° < PI < 37.9°		[33.7 to 37.9]	[−1.5 to 13.3]	[21.2 to 38.5]	[41.2 to 62]	[22.5 to 51.5]
II	44	42.7 ± 2.8	8.9 ± 4.8	33.8 ± 4.8	55.5 ± 8	48 ± 8.8
38° < PI < 47.9°		[37.9 to 47.6]	[−5.1 to 18.2]	[23.1 to 48.4]	[41.5 to 76.5]	[24 to 64.7]
III	59	52.6 ± 2.8	12.5 ± 5.6	40.1 ± 5.5	61.5 ± 8.4	47.4 ± 10.7
48° < PI < 57.9°		[48.2 to 57.4]	[−1.2 to 23.2]	[28.2 to 52.9]	[43.1 to 81.9]	[24 to 70.3]
IV	26	62.6 ± 2.8	15.8 ± 4.3	46.8 ± 4.2	68.3 ± 5.1	47.6 ± 7.8
58° < PI < 67.9°		[58.2 to 67.6]	[7.1 to 26.8]	[37.9 to 58.5]	[60.9 to 76.3]	[34.7 to 64.7]
V	11	72.6 ± 2.8	19.7 ± 5.5	52.9 ± 5.2	74.9 ± 6.8	46 ± 10.2
68° < PI < 77.9°		[69.6 to 77.4]	[12.6 to 27.9]	[46.2 to 59.6]	[62.2 to 81.6]	[29.7 to 62]
VI	2	81.4 ± 3.3	21.9 ± 12.3	59.5 ± 9	76 ± 8.3	44.6 ± 12.2
78° < PI < 87.9°		[79.1 to 81.4]	[13.2 to 30.6]	[53.1 to 65.9]	[70.1 to 81.9]	[36 to 53.3]

Table 2 Theoretical normal values for spino-pelvic parameters

PI group	PI interval	Theoretical PT	Theoretical SS	Theoretical LL
I	<38	4	30	PI + 20
II	38–48	8	35	PI + 15
III	48–58	12	40	PI + 10
IV	58–68	16	45	PI + 5
V	68–78	20	50	=PI
VI	>78	24	55	PI − 5

lumbar kyphosis. In a previous work, we also found that patients with degenerative disc disease and disc herniation were characterized by flat spine with significant reduction of both lumbar lordosis and thoracic kyphosis. This profile was more marked for patients with disc diseases below 45 years old [2]. Our findings were concordant with those reported by Rajnics et al. [19] through a similar study. When the spine is too much rigid (aging of the spine is kyphosis and ankylosis), there is no possibility for the patient to reduce the magnitude of the thoracic curve.

Hyperextension of adjacent segments

Hyperextension of adjacent segments is a very common local compensatory mechanism to limit the consequences of lumbar kyphosis on the shift of axis gravity (Fig. 5). Previous studies demonstrated that low back pain subjects were characterized by less distal lordosis, a more vertical sacrum and more proximal lumbar lordosis [8, 12]. More proximal lumbar lordosis signified more extension in the upper lumbar spine. Recently, Schuller et al. [22] found that upper lumbar spine (L1–L2 and L2–L3 segments) was more extended for patients with L4–L5 degenerative spondylolisthesis. Hyperextension can be global (multi-segmental) or really local (mono/bi-segmental). Local hyperextension is efficient to place posteriorly the upper spine, however, this generates increase of stresses on posterior structures (Fig. 5), exposes to the risk of retrolisthesis and may result in accelerated facet joints arthritis, inter-spinous hyper pressure (Baastrup disease) and sometimes isthmic lysis.

From a biomechanical point of view, we assume that compensatory discopathy has to be differentiated from classical aging discopathy (Fig. 6). Compensatory discopathy is characterized by a discal hyperextension, more than 15°, compensating a loss of lordosis. On the opposite aging discopathy (the most frequent type) is characterized by a disc narrowing with parallel endplates resulting in loss of lordosis. The sagittal orientation of disc space (extended, neutral, kyphotic) is therefore very important to consider when analyzing consequences of degenerative discopathy on global balance.

Retrolisthesis

Retrolisthesis, defined as the posterior slippage of the upper vertebra in reference to the lower vertebra, are typically limited to 2–3 mm slippage in the lumbar spine. It often results in severe foraminal stenosis and more rarely in central stenosis (Figs. 4, 5). Retrolisthesis is usually observed at the immediate adjacent segment(s), lower or upper, of the kyphotic spine: L5–S1 and upper lumbar spine (L1–L2 and L2–L3) are common sites. Retrolisthesis is typically underestimated on lying down radiological imaging techniques (CT scan and MRI), however, it can be suspected on MRI imaging in the presence of sub-luxation of facet joints with fluid collection (Fig. 4).

Pelvis area

The only compensatory mechanism in the pelvis area is pelvis back tilt (also called pelvis retroversion) defined by the increase of the pelvis tilt and corresponding to the posterior

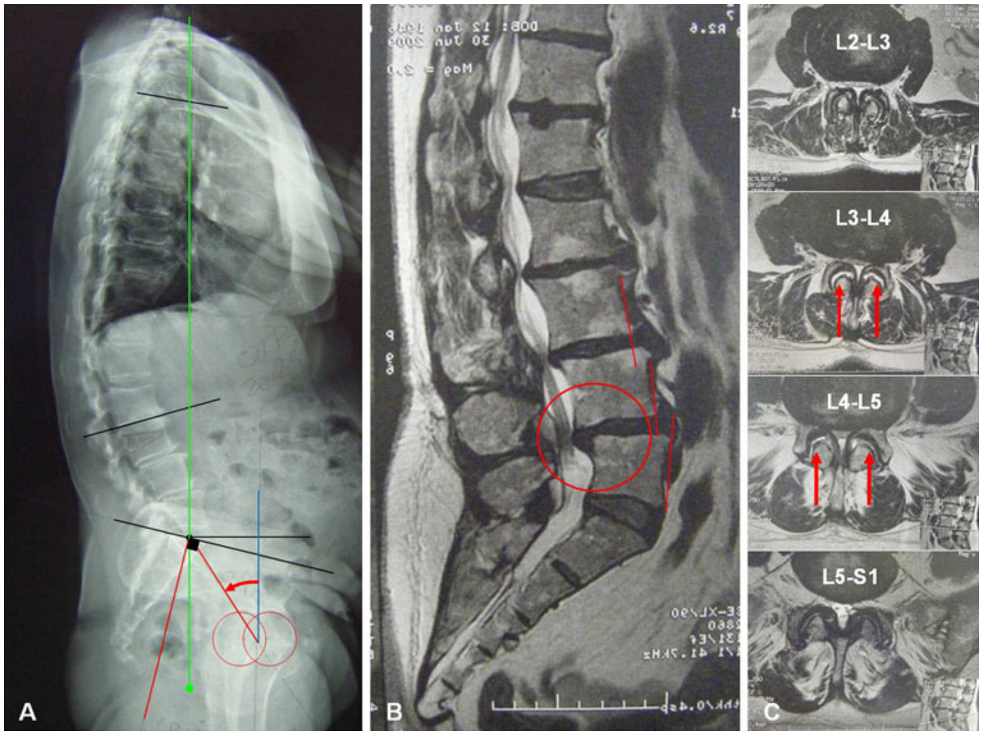

Fig. 4 Patient with lumbar kyphosis and severe multilevel stenosis from L2–L3 to L4–L5: full spine radiographs (**a**), sagittal T2-weighted (**b**) and transverse T2-weighted (**c**) MRI sequences. The patient is still balanced (C7PL/SFD is 0.25) but balance is compensated by three main mechanisms: pelvis back tilt (*curved arrow*), multilevel retrolisthesis (*red circle*) and reduction of thoracic kyphosis (calculated to 25°). PI was measured to 47°, PT was 34° and SS was 13°. Compared to group control from normal and asymptomatic population, we should expect value of PT around 10°. On MRI axial slices, retrolisthesis at L3–L4 and L4–L5 are associated with fluid collection in facet joints (*straight arrows*)

rotation of the pelvis around the femoral heads, similar to that during hip extension (Fig. 7). This motion is consecutive to contraction of the hip extensor muscles and results in posterior positioning of the sacrum related to the coxo-femoral heads. Bringing back the sacral plate related to the coxo-femoral heads and increasing the sacro-femoral distance, this mechanism permits to compensate the anterior translation of the axis of gravity. The pelvis incidence determines the global capacity of pelvis retroversion, which is easily achieved for patients with a great pelvic incidence. In fact, considering that $PI = SS + PT$, and that SS cannot be a negative number, you can tilt more with a high PI than with a low PI, since there is a much wider range through which adaptation can occur. Numerous studies reported that patients with chronic low back pain and lumbar degenerative disease were characterized by decrease of sacral slope and increase of pelvis tilt [2, 8, 12] as demonstrated in our illustrated case in Fig. 4.

Lower limbs area

Knee flessum

Knee flessum is a well-known compensatory mechanism for patients with severe degenerative spine and has already been widely reported [10] (Fig. 8). More recently, I Obeid and JM Vital demonstrated the strong correlation between knee flessum angle and the lack of lordosis (which was estimated from the theoretical lordosis) [18].

Ankle extension

Through a prospective study Lafage et al. [14] recently underlined that the pelvis translation was a parameter as important as the pelvis rotation (measured by the pelvis tilt) and probably induced by extension in ankle joint. Therefore, they suggested that our patients should be analyzed from head to feet.

Algorithm

Finally we propose a three steps algorithm to achieve the analysis of sagittal balance and determine the presence or not of compensatory mechanisms:

First step what is the value of the pelvis incidence? The knowledge of the pelvis incidence permits to determine the expected theoretical values of the spino-pelvic positional parameters (Tables 1, 2).

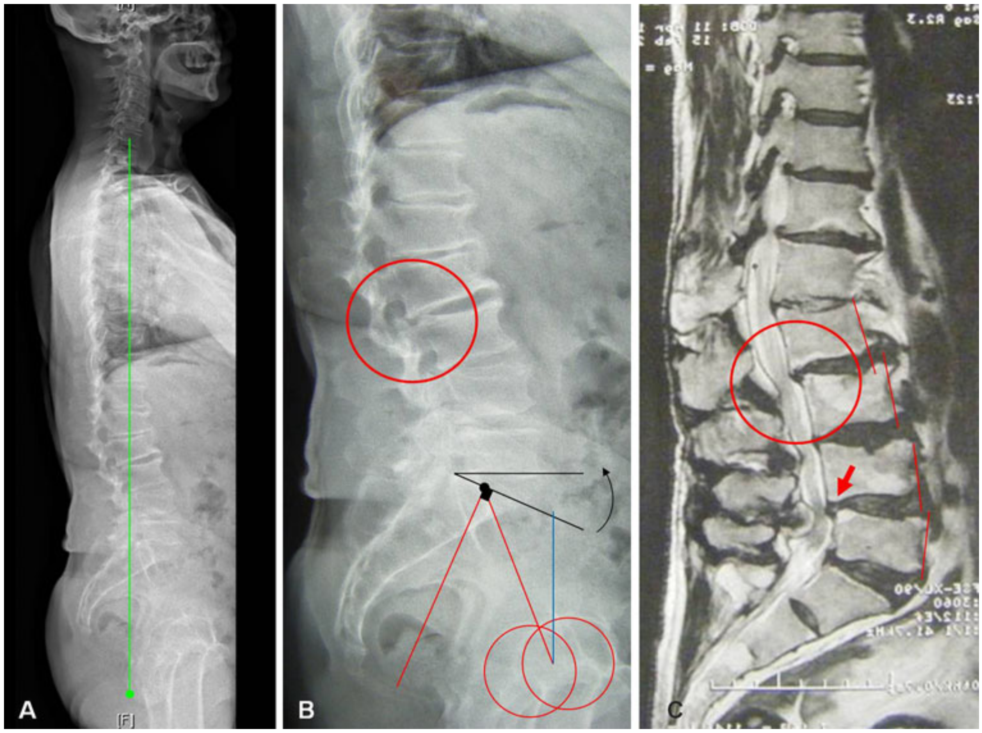

Fig. 5 Patient with lumbar stenosis from L2–L3 to L4–L5 and thoraco-lumbar kyphosis: full spine radiographs (**a**), X-rays focused on lumbo-pelvic zone (**b**) and sagittal T2-weighted MRI sequence (**c**). The patient is well balanced (C7PL/SFD is −0.3) however some compensatory mechanisms are present in the lumbar area. Hyperextension is observed at L5–S1 (*curved black arrow*) (local lordosis was measured to 24°) and there are multilevel retrolisthesis at L2–L3 (*red circle*) and L4–L5 (*large arrow*). The pelvis tilt was quite normal as it was calculated to 22° and the PI to 46°

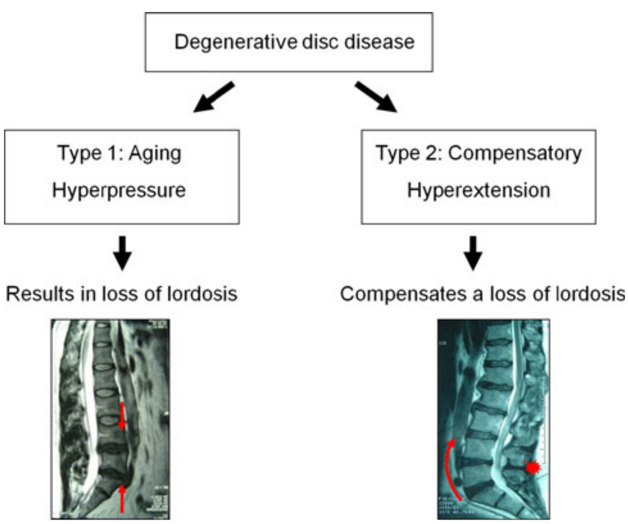

Fig. 6 Classification of degenerative disc diseases into aging discopathy and compensatory discopathy

Second step is the patient globally balanced? Global sagittal alignment is evaluated by analyzing the positioning of C7, related to the sacrum, using measurement of SSA and/or C7PL/SFD ratio.

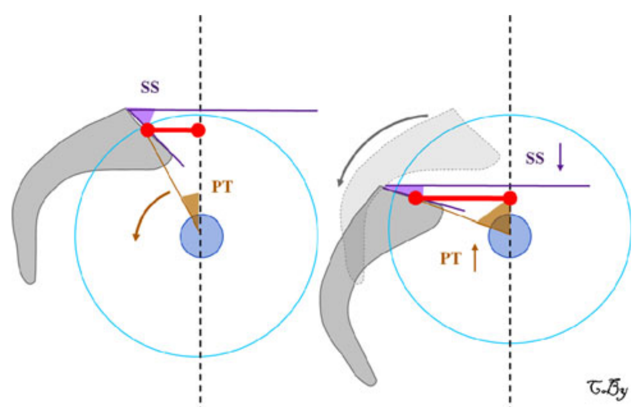

Fig. 7 Pelvis back tilt mechanism. Increase of pelvis tilt results in posterior placement of sacrum related to the coxo-femoral heads thus increasing the sacro-femoral distance (*red line*)

Third step are there some compensatory mechanisms? In spinal area: analysis of this zone consists of measurement of lumbar lordosis and thoracic kyphosis and looking for the presence of compensatory discopathy (ies) and retrolisthesis. Cervical curvature analysis should also be included.

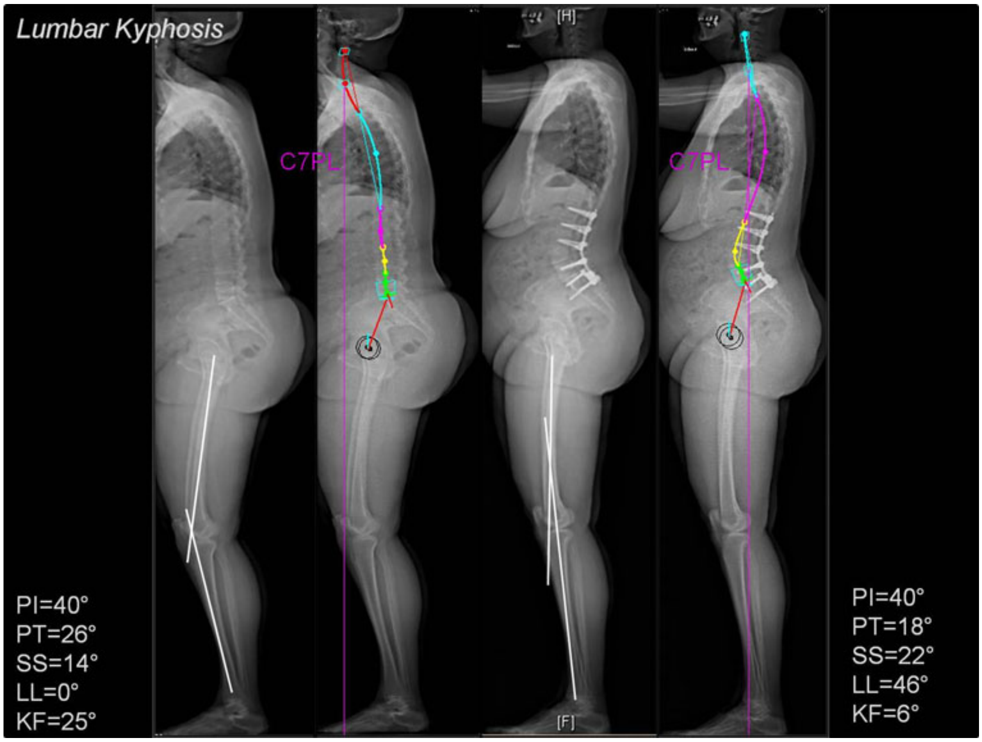

Fig. 8 Illustrative case with lumbar kyphosis and compensatory knee flessum. After surgical correction of the kyphosis (TPO procedure at L4) the knee flessum significantly reduced postoperatively suggesting the improvement of the global sagittal balance. Return to a more physiologic thoracic curve was also observed

In pelvic area: Is the pelvis tilt (PT) adequate with respect to the pelvis incidence? The presence of horizontal sacral plate is highly suspected of pelvis back tilt mechanism.

In lower limbs area: Are the knee flexed? One must care to this point considering that knee flessum minimizes the importance of sagittal imbalance on full spine radiographs. Measurement of knee flessum angle is mandatory.

Conclusion

Meticulous and exhaustive analysis of spino-pelvic parameters allows for identification of the main compensatory mechanisms observed in patients with sagittal balance disorders. Although the compensatory mechanisms are efficient to limit the sagittal unbalance, they could result in adverse effects such as mechanical pain and compromise of neurological structures. These mechanisms have to be considered prior to therapeutic options. This may probably optimize the management of patients with severe degenerative spine especially when surgical treatment with instrumentation of the spine is planned.

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Conflict of interest None.

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