



Sagittal plane alignment of the spine and gravity A radiological and clinical evaluation

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Analysis of the sagittal balance of the spine includes the study of the spinal curves and of the pelvis in the sagittal plane. It therefore requires full-spine lateral radiographs. The sagittal balance of the spine was studied in forty-nine young adults. Strong correlations were observed between parameters related to the pelvis (“pelvic incidence angle”, “sacral slope” and “pelvic tilting”), and the sagittal spinal curves (“lordosis” and “kyphosis”). We therefore propose to begin the evaluation of the sagittal plane alignment of the spine in clinical practice with measurement of the pelvic incidence angle. The relationship between the pelvic incidence angle and the sacral slope, as well as between the sacral slope and lordosis, is then assessed, and these are related to each other. The use of a graphic abacus facilitates assessment of the physiological comparison of the measured values and of the relationship between pelvic and spinal parameters, within their range of physiological variability. This analysis of the sagittal alignment of the spine also considers its dynamic aspect and the importance of gravity load and of muscular contraction on the lumbar structures. These data have been published previously and are recalled here.

Three basic patterns of disruption of the relations between parameters may be encountered : a sacral slope angle exceeding the value expected considering the measured pelvic incidence angle (owing to fixed flexion contracture of the hips), excessive lordosis with regard to the observed sacral slope angle (with hyperkyphosis at the thoracic level) and stiff hypolordosis with pelvic retroversion. These three conditions are analysed in the light of the repercussions of the gravity load on the lumbar structures.

A convenient method is thus available for functional analysis of the sagittal balance of the spine.

INTRODUCTION

Accurate analysis of the morphology of the spine in the sagittal plane is essential to adequately treat its pathology. Numerous descriptive studies exist in the literature, where multiple sagittal postures are described, characterised by a combination of lordosis and kyphosis of variable degree. The large dispersion of the values measured for these curves is attributed to human disparity (5, 27). Their clinical use remains illusory, as none of these studies has investigated the interaction between these data and the clinical features. Some studies have pointed out the interconnection between the pelvis and the spine, but none has described any relation

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between positional and morphologic pelvic parameters (5, 10, 16, 17, 28, 29, 30).

We have established in previous publications the correlation between radiographic pelvic parameters (positional and anatomical) with the spinal curves and with barycentremetric data (i.e. the point of application of the gravity load on the disco-vertebral structures) (6, 20, 22).

We recommend here an analytic assessment of the sagittal alignment of the spine and of its individual adaptability, established from radiographic parameters and taking into account the gravity line. It is intended to be readily applicable in daily clinical practice.

MATERIALS AND METHODS

Forty-nine young adults, 28 male and 21 female, free of any spinal pathology, were investigated. Their mean age was 24 years (range : 19 to 30).

The spinal shape in the sagittal plane was analysed on full-spine lateral radiographs taken in the upright position, including the pelvis and the femoral heads. The patients were lying horizontally on a support with the arms flexed 90°.

Various parameters were measured using the dedicated software "Rachis 91", developed by Hecquet (12, 15). An ultrasonic digitiser (GP-7 Grafbar) was used to determine on the radiographs the cartesian coordinates of the four corners of each vertebral body, of the superior sacral plate and of the femoral heads. These data were recorded in the computer. The midpoint of the line connecting the centres of the two femoral heads, considered as the sagittal projection of the midpoint of the distance between the hips, was calculated by the software.

Previous studies of the gravity loads

The gravity loads on the vertebral and pelvic structures were assessed using the "barycentrometer". The barycentrometer is an experimental scanner that permits calculation of the location of the gravity center of body slices by absorption of gamma-rays. Computed integration of these data and connection to the software "Rachis 91" give us the cartesian coordinates of the center of gravity of the body segment represented by each vertebral structure, and by the femoral heads, with the patient in the upright position. Technical data and validation of the method have been published (2, 3, 7, 8).

This "barycentremetry" was previously performed for each subject. Consequently, the sagittal lever arm of gravity on each vertebra was available for each subject.

The relations between these barycentremetric data and the following radiographic parameters were analysed.

Radiographic sagittal parameters

All are angular values, expressed in degrees, and therefore independent of radiographic magnification. A positive value is posterior, a negative value anterior.

The *pelvic parameters* are : (fig 1)

- the anatomical parameter "incidence" : the angle between the line perpendicular to the sacral plate at its midpoint and the line connecting this point to the midpoint between the femoral heads.

It is an anatomical parameter, specific to each individual and independent of the spatial orientation of the pelvis (the mobility of the sacroiliac joint being considered negligible). It was not observed to differ significantly according to age or gender, once growth has been completed (4, 6, 20, 22, 24, 25).

The orientation of the pelvis is expressed by :

- the sacral slope : the angle between the upper plate of S1 and the horizontal line.
- the pelvic tilt : the angle between the vertical and the line connecting the midpoint of the upper plate of S1 to the middle of the femoral heads.

Geometrically, by complementary angle constructions, the anatomical parameter "incidence" is the algebraic sum of the "pelvic tilt" and the "sacral slope".

The *spinal parameters* are :

- lordosis : the angle between the superior sacral plate and the most posteriorly tilted vertebral plate.
- kyphosis : the angle between the superior sacral plate and the most anteriorly tilted vertebral plate.

The *tilts* (fig 2)

- L1 tilt : the angle between the vertical and the line connecting the midpoint of the upper plate of S1 to the midpoint of the upper plate of L1
- T9 tilt : the angle between the vertical and the line connecting the midpoint between the femoral heads to the centre of the vertebral body of T9.



Fig. 1. — The pelvic parameters. *Incidence* : the angle between the line perpendicular to the sacral plate at its midpoint and the line connecting this point to the middle of the femoral heads. *Sacral slope* : angle between the upper plate of S1 and the horizontal line. *Pelvic tilt* : angle between the vertical line and the line connecting the midpoint of the upper plate of S1 to the femoral heads.

The barycentremetric data indicate that the centre of gravity of the body segment supported by the femoral heads is located anterior to T9 (2, 6, 8). The tilt of T9 was therefore suggested as a substitution parameter for the global balance of the trunk above the femoral heads. L1 tilt reflects the lumbar balance.

RESULTS

Previous barycentremetric data (2, 8, 9, 21, 23)

Previous studies demonstrated that the gravity centre of the body segment supported by the femoral heads is located in front of T9, ± 1.5 cm anterior to the vertebral body if the kyphosis is more than 30° , less if the kyphosis is less than 30° . The projection of this gravity centre is 36.2 mm (S.D. 20.6) behind the line connecting the centers of the femoral heads. This expresses an optimal economic balance : under such conditions, no muscular electric activity is observed in the posterior spinal muscles. On the contrary, if anterior tilt of the trunk occurs and the projection of the gravity centre becomes more anterior, muscular activity in the posterior musculature is detected.

Moreover, it was observed that the centres of gravity of the body segments supported by the vertebrae were included in a vertical cylinder of ± 1 -cm diameter, located very close to the spine, ante-

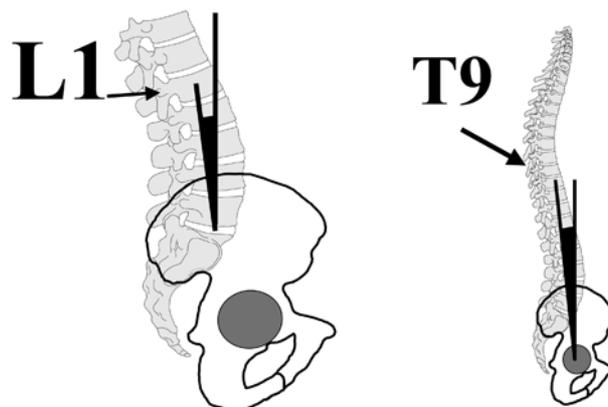


Fig. 2. — The tilts. *Tilt of L1* : angle between the vertical and the line connecting the middle of the upper plate of S1 to the middle of the upper plate of L1. *Tilt of T9* : angle between the vertical and the line connecting the centre of the axis of the femoral heads to the centre of the vertebral body of T9.

riorly at the thoracic levels and posteriorly at the lumbar levels, when the balance is optimal, as in healthy subjects.

Radiographic parameters (6, 13, 20, 22, 23)

The mean values and standard deviations of the radiographic parameters are expressed in table I.

Several strong correlations exist between these pelvic and spinal parameters (6, 20, 22) (fig 3).

Firstly, a very strong correlation ($r = 0.83752$) exists between the values of the “sacral slope” and of the “pelvic incidence” :

$$\text{sacral slope} = (\text{pelvic incidence} \times 0.5481) + 12.7^\circ (\pm 6.39^\circ).$$

Therefore the orientation of the pelvis, expressed by the sacral slope, is closely determined by the pelvic morphology in the sagittal plane, represented by the “pelvic incidence”.

Moreover, lordosis is closely dependent on the sacral slope ($r = 0.85943$) :

$$\text{lordosis} = (\text{sacral slope} \times 1.087) + 21.61^\circ (\pm 4.16^\circ).$$

Therefore, the sagittal spinal curve “lordosis” is closely linked to the pelvic morphology and is specific for each individual. A low value for the pelvic

Table I. — Mean values (and standard deviations) of the radiographic sagittal pelvic and spinal parameters (positive value is posterior, negative is anterior)

Parameters	Mean	SD
Incidence (°)	53.4	11
Sacral Slope (°)	-41.7	8.2
Pelvic tilting (°)	-12	6.7
Lordosis (°)	60.9	10.5
Kyphosis (°)	-45.5	9.7
Tilt T9 (°)	11.2	3
Tilt L1 (°)	-8.7	5.1

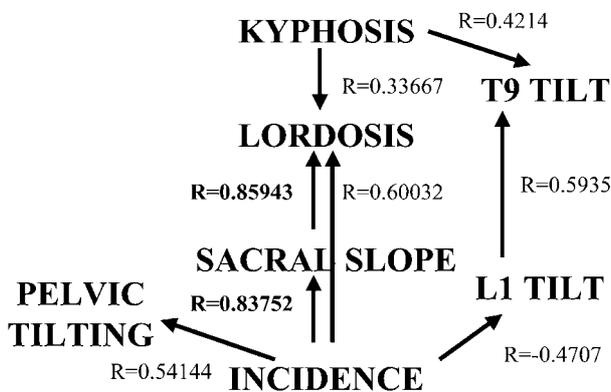


Fig. 3. — The significant correlations between the positional pelvic and spinal parameters and the morphological pelvic incidence.

incidence angle implies low values for the sacral slope and decreased lordosis ; a high value for the pelvic incidence angle implies a markedly tilted pelvic orientation and pronounced lordosis.

The strict connections between pelvic incidence, sacral slope and lordosis are graphically expressed in fig 4. It is useful to assess the relations between these parameters in clinical practice.

DISCUSSION

There is an obvious interdependence between the spinal curves and the orientation of the pelvis. Evaluation of the spine in the sagittal plane for one specific individual consists of checking the relationships between the parameters described above, within the range of normality for the values of each of them.

It is convenient to start with measurement of the anatomical parameter “pelvic incidence”. The observation of a low value for pelvic incidence entails a risk that the balance obtained will be difficult to maintain, as the range of adaptation for the pelvis is limited, should a perturbation occur. On the other hand, high values for pelvic incidence were observed in cases with progressive spondylolysis (1, 14, 25).

The second step consists of applying the equation relating the “pelvic incidence” to the sacral slope ($sacral\ slope = (incidence \times 0.5481) + 12.7$), and comparing the values thus calculated with the observed values, accepting a range of variability of $\pm 6.39^\circ$. For example, for a measured «pelvic incidence» of 53° , the ideal sacral slope will be $40^\circ (\pm 6.39^\circ)$, with a range from 34 to 46° . A high “incidence” corresponds to a very tilted sacral slope. For example, a high “incidence” of 80° implies an adapted sacral slope of 50 to $62^\circ (56.6^\circ \pm 6.4)$. Similarly, a low “incidence” implies a more horizontal sacral slope : for an “incidence” of 30° , a sacral slope of 23 to $35^\circ (29.1^\circ \pm 6.4)$ is physiological.

The third step consists of testing the adequacy of the relationship between sacral slope and lordosis ($lordosis = (sacral\ slope \times 1.087) + 21.61$, with a range of variability of $\pm 4.16^\circ$). For example, the suitable value for lordosis, with a sacral slope of 40° , is $65.1^\circ (\pm 4.16^\circ)$, with a range from 61° to 69° .

The kyphosis angle will then be measured in order to determine if falls within the physiological range of values. If not, it is either a flat back or a hyperkyphosis, the origin of which must be determined. Kyphosis itself will indeed have repercussions on the inferior levels of the spine.

The use of the abacus (fig 4) allows for easy and quick assessments, and at the same time determines if the values fall within the physiological range (determined as “normal”) and assesses the relationship between parameters. Note that a value outside the norms for sacral slope or for lordosis will not necessarily be the origin of sagittal disruption, but may reflect compensation of an anomaly located in the lower limbs, or at another spinal level.

Three typical patterns of perturbation of the sagittal balance between parameters should be considered.

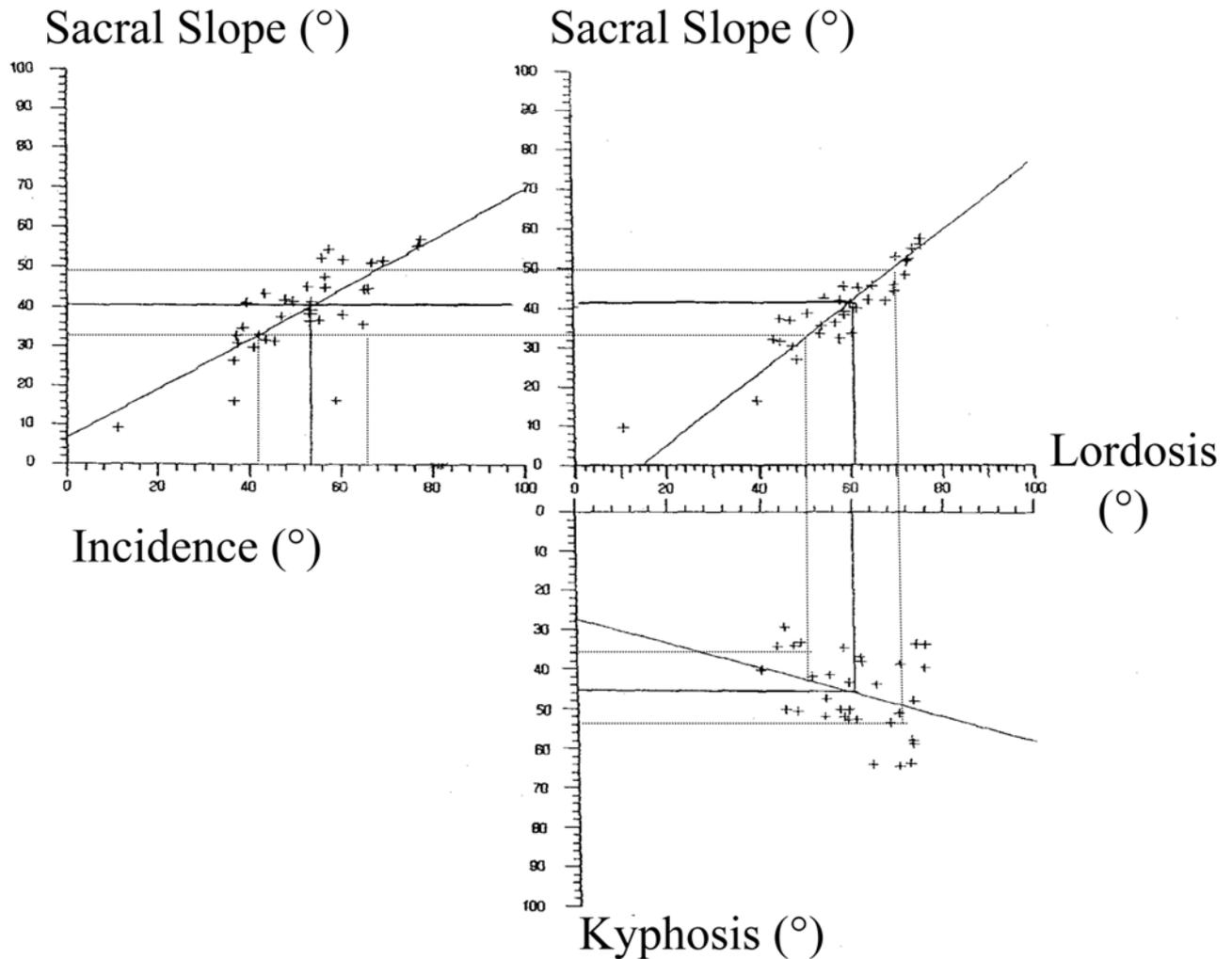


Fig. 4. — Abacus of the physiological range of variability of the parameters : incidence, sacral slope, lordosis and kyphosis. Graphical visualisation of their respective relationships : sacral slope = (incidence \times 0.5481) + 12.7 \pm 6.39° $r = 0.83752$ and lordosis = (sacral slope \times 1.087) + 21.61 \pm 4.16° $r = 0.85943$.

– The first one is a sacral slope conforming to the value determined by the «pelvic incidence» (example : the sacral slope is 45° for a «pelvic incidence» at 55°) but with an observed value for lordosis which is excessive with regard to the theoretical value calculated according to the sacral slope (the observed lordosis is 85°, but the theoretical value is between 66° and 74° for this example). The relative relationship between the pelvic parameters indicates that the pathologic phenomenon occurs at another level. In this example, the hyperlordosis observed is the compensation of excessive kypho-

sis in the upper spinal segments. The process of assessment has therefore first evaluated the pelvic interactions, then the spinal one, in order to determine the influence of the kyphosis, down on the lumbar curvature.

– The second pattern is an observed sacral slope excessive with regard to the value determined by the “pelvic incidence” (example : the observed sacral slope is 56°, but the measured “pelvic incidence” at 55° implies a value for the sacral slope between 36° and 49°). Nevertheless, in this pattern, the significant lordosis (84° in the example) is

adapted to the observed sacral slope (theoretical value between 79 and 87° for a sacral slope at 56°). In this situation, the relationship between sacral slope and lumbar curvature is respected: the disruption is not spinal but pelvic. This excessive sacral slope results from a flexion deformity of the hips, whatever its origin (osteoarthritis, capsular or muscular retractions, knee pathology). The excessive value for lordosis reflects the spinal compensation of this excessive slant of the pelvis. It is worth noting that achieving such marked lordosis may not be possible for some individuals. Consequently, the balance of the spine will tend to be forward due to this insufficient compensation. On the other hand, an excessive lumbar curvature will be harmful for the posterior articular processes of the vertebrae and result in degenerative lesions (and pain).

≤— The third pattern is a lower value of sacral slope with regard to the parameter “pelvic incidence”, which implies a more important value, for example, a 20° sacral slope in a case where it should be between 36° and 49° , according to a 55° “pelvic incidence”, and a low value for lordosis (44°). In this case, the disruption is caused by a stiff hypolordosis (such as in a flat back fusion) that forces the pelvis to a horizontalisation of the sacral slope to keep the trunk from tilting forward (20, 21, 22, 23).

In clinical practice, several patterns may be combined, such as the association of stiff hypolordosis and osteoarthritis with flexed hips (6, 10, 16, 17, 18, 19).

Interpretation of the sagittal shape of the spine also necessitates appreciating the quality of the balance obtained in terms of the muscular contraction needed for its maintenance (fig 5). Indeed, the relationship between parameters involves more than simple radiographic measurements. It also reflects a dynamic balance of muscular synergies. Each situation will be more or less economical in terms of muscular effort and of forces exerted on the discal and ligamentous structures. This is shown by electromyographic study of the posterior spinal muscles: no muscular contraction is noted when the relationship between sacral slope and “pelvic

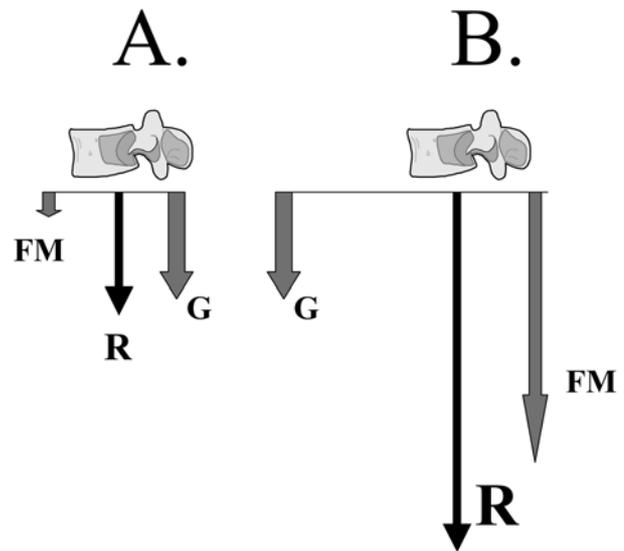


Fig. 5. — The balance between gravity and compensatory muscular forces. A. *Economic balance*: the gravity force is posterior to the axis of the vertebra and no muscular contraction is needed. B. *Uneconomic balance*: the anterior location of gravity (and its lever arm) requires posterior muscular contraction for compensation, both increasing the load on the disc.

incidence” is harmonious, but a muscular compensatory effort is observed when this relationship is unsettled. If an anterior slant of the trunk occurs, the gravity forces supported by the lumbar and pelvic structures are projected forward. The stresses are therefore increased on these structures, owing to both the longer anterior lever arm of gravity and the compensatory activity of the posterior spinal musculature. In these cases, the sagittal balance could be qualified as uneconomical, or pathological (6, 8, 9, 11, 20, 21, 22, 23, 26).

It is thus advisable to understand the analysis of the sagittal spinal shape as an evaluation of the balance between gravity and muscular activity. As the gravity centre of the bodily segment supported by the femoral heads (reflecting the global spino-pelvic balance) was noted to be anterior to T9, the “tilt of T9” appears as an alternative parameter indicating the sagittal condition of the spine and the pelvis, as the “tilt of L1” for the lumbar levels above the pelvis.

Meticulous analysis of the lumbar levels allows evaluation of the gravity forces exerted on these

structures. Indeed, the gravity line was observed to remain relatively vertical, anterior to the thoracic vertebrae, but posterior to the lumbar vertebrae and the femoral heads. It is the respective arrangement of the body slices that results in the achievement of the best possible balance. This arrangement tends to compensate for a possible disruption, by pelvic rocking and/or accentuation (or flattening) of the curves, principally the lumbar curve. Reduction of lumbar lordosis will induce a relative posterior translation of the disco-vertebral structures. The latter will therefore be located behind the gravity line, in an unfavourable situation with respect to the mechanical lever arm of gravity and the posterior muscular forces, resulting in accentuation of the pressures on the discs.

Thus, the basic patterns individualised thanks to the analyses of the parameters are to be reconsidered with regard to the gravity line. In the first pattern, accentuation of the kyphosis induces an anterior displacement of the gravity line into the upper body. To compensate, in order to bring back the gravity line to its normal position, (to restore a good global balance behind the femoral axis), the subject will accentuate lordosis, within the limits of his possibilities. If this manoeuvre is insufficient, he will tilt his pelvis backwards. This rocking permits to reposition the gravity line more posteriorly behind the femoral heads, and at the same time it advances the femoral heads relative to the sacral plate and tilts the upper-lying trunk posteriorly. However, in this compensatory situation, the global balance is improved but the balance at the lumbar levels will be made worse by posterior translation of the disco-vertebral structures relative to the gravity line. This excessive stress will result into degenerative lesions. Pain is also attributable to the chronic muscular efforts needed to achieve relative stabilisation. This is also the case for the subjects presenting with stiff hypolordosis with a low sacral slope of the third pattern.

For the second pattern with retraction of the hip, the global gravity is also too anterior at both the lumbar and femoral levels, owing to excessive pelvic anteversion and anterior slant of the body. The sole possible compensation is in the spine: accentuation of the lordosis. If this is insufficient,

the balance will be unfavourable, both for the lumbar levels and for the global body relatively to the femoral heads. If the subject compensates by flexion of the knees, the situation will be improved at the global body level, but will not be bearable for a long time. A cane as support is useful for relief.

Modifications in the body masses also influence these balances between gravity and muscular activity. An increase in the abdominal mass (pregnancy, weight gain, abdominal distension) is deleterious. The compensation of such an anterior projection of gravity by an excessive accentuation of lordosis can be detrimental for the posterior articular processes. This option necessitates good abdominal musculature. The other compensatory option is flattening of the lumbar curvature and pelvic retroversion. It will be inadequate in terms of the lever arm of gravity on the lumbar structures, as described above. Moreover, this condition will be accentuated if there is relative amyotrophy of the posterior spinal muscles, classically occurring in aging individuals. This posterior amyotrophy contributes to the forward displacement of gravity.

CONCLUSION

Analysis of the spinal balance in the sagittal plane appears to be descriptive and functional. Assessment of the relationship between the radiographic parameters must be integrated with the notion of dynamic balance between gravity and the muscular forces. Any disruption of the balance, at any level, induces some compensatory reactions of this whole organ including the spine and the pelvis (and the lower limbs). The assessment of every sagittal shape must consider both the values and the relationship of every parameter in the physiological range of global balance, and the location of the lumbar levels in the sagittal plane relative to the pelvis and to the gravity line.

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