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Sagittal morphology and equilibrium of pelvis and spine

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Abstract A prospective analysis of the sagittal profile of 100 healthy young adult volunteers was carried out in order to evaluate the relationship between the shape of the pelvis and lumbar lordosis and to create a databank of the morphologic and positional parameters of the pelvis and spine in a normal healthy population. Inclusion criteria were as follows: no previous spinal surgery, no low back pain, no lower limb length inequality, no scoliotic deviation. For each subject, a 30×90-cm sagittal radiograph including spine, pelvis and proximal femurs in standing position on a force plate was performed. The global axis of gravity was determined with the force plate. Each radiograph was digitized using dedicated software. The spinal parameters registered were values for thoracic kyphosis and lumbar lordosis. The pelvic angles measured were:

pelvic incidence, sacral slope and pelvic tilt. The global axis of gravity was on average 9 mm anterior of the center of the femoral heads. The anatomic parameter of pelvic incidence angle varied from 33° to 85° (mean: 51.7°, SD: 11°). The average lumbar lordosis was 46.5°. The average thoracic kyphosis was 47°. We found a statistical correlation between incidence angle and lumbar lordosis ($r=0.69$, $P<0.001$) and between sacral slope angle and lumbar lordosis ($r=0.75$, $P<0.001$). Spine and pelvis balance around the hip axis in order to position the gravity line over the femoral heads. We propose a scheme of sagittal balance of the standing human body.

Keywords Sagittal balance · Gravity axis · Pelvic incidence angle · Lordosis · Kyphosis

Introduction

Studies of sagittal balance of volunteer subjects in the standing position have been previously published [1, 7, 8, 9, 10, 11, 12, 17, 18, 20, 21]. Generally, these studies have used different ways to determine the axis of gravity and to analyze lumbar lordosis and sagittal spinopelvic angulation. It is well known that there is a correlation between the inclination of the sacral end and the lumbar lordosis [17].

On the other hand, rotation of the pelvis around the bi-coxofemoral axis regulates the lumbar lordosis [3]. The preservation of a “good” lumbar lordosis seems to be an

important factor in maintaining a favorable long-term outcome after spinal arthrodesis [16]. However, it is still not clear how the optimal lordosis for each person can best be qualified and quantified. Up to now, only a few studies of global sagittal assessment of the trunk with normal volunteers have been performed. Relations between the pelvic anatomy and lumbar lordosis have been described by Duval-Beaupère and colleagues [6, 13]. These authors focussed on a fundamental anatomical pelvic parameter: the pelvic incidence angle. They reported a significant correlation between the pelvic incidence angle and lumbar lordosis, and it seems that lumbar lordosis is closely linked to the shape of the pelvis.

In this study, using Duval-Beaupère's pelvic angles, the standing spinopelvic balance was analyzed in young adult volunteers. Dynamic, morphologic, and positional parameters of the sagittal balance were analyzed. Using a customised instrumental measurement method, we were able to obtain a more accurate assessment of the position of the global axis of gravity. This led to an improved understanding of the mechanism of sagittal balance, by demonstrating the influence of the pelvic shape on the pelvic and spinal position.

Furthermore, we wished to obtain a data bank of positional and morphologic parameters of pelvis and spine in a young healthy population. In further studies, it will be possible to compare this normal population with pathologic populations and to check the variations of shape and balance in spinal disorders.

Materials and methods

We studied 112 normal volunteers, recruited mainly from medical and paramedical students at our institution (physicians, nurses, physiotherapists). All subjects signed their informed consent. Inclusion criteria were as follows:

1. Age between 20 and 45 years old
2. No previous history of spinal disorder or spinal surgery
3. A normal physical examination with no evidence of leg length discrepancy or scoliotic deformation

For each subject, a 30×90-cm standing radiograph, including the spine, pelvis and proximal femurs, was obtained. Each radiograph was analyzed separately by two physicians, and subjects were excluded from the study if any radiological abnormality was found. Twelve subjects were thus excluded for the following asymptomatic radiological abnormalities: four L5-S1 isthmic spondylolyses, two grade II spondylolistheses, five thoracolumbar kyphoses (Scheuermann's disease) and one supernumerary lumbar vertebra.

The final population available for review was therefore composed of 100 subjects, who were clinically and radiographically normal. The sex ratio was 54% male and 46% female; the mean age was 26.5 years old (minimum 23 years, maximum 45 years, standard deviation 4 years).

The prospective radiological protocol used in this study was the same one as is used routinely at our institution for patient evaluation: a left to right 30×90 cm lateral radiograph, in a comfortable standing position, the knees fully extended, the upper limbs resting on two arm supports. Each subject stood on a force plate (Tefal SA, Rumilly, France) that determines the coordinates of the ground projection of the global axis of gravity. The gravity measurement was obtained simultaneously with the radiograph. The X-ray source, the middle of the force plate and the middle of the radiological film were on the same alignment. The distances between X-ray source, force plate and radiological film were known and constant. The vertical position of the radiological source and film were adaptable to the subject's size. The source was always indexed on the middle of the film (Fig. 1). The radiographs were digitised using a Vidar VXR8 X-ray film scanner (View-tec, Saint-Maurice, France). The radiological measurements were performed using dedicated software [2]. By a homothetic projection, the software calculated the position of the global axis of gravity on the radiograph.

We used an original geometrical model of the thoracic and lumbar spine. This model is based on elementary geometrical constructions, namely tangent arcs of circle and straight lines. The sagittal shape of the spine was considered as a succession of curved segments (thoracic kyphosis and lumbar lordosis), united by a straight thoracolumbar segment (Fig. 2A). Each curve was modelled by two tangent arcs of circle (Fig. 2B,C). Using this method, the construction of the spinal model was obtained by pointing to five points and three tangents on the anterior vertebral bodyline on the digitised radiographs. Each modelled sagittal curve was characterised by its length, by the number of vertebral units included and by the angular value of each arc of circle.

The pelvic measurements were the pelvic parameters defined by Duval-Beaupère and colleagues (Fig. 3, Fig. 4). The sacral end, in our studied population, was always well visualised as a straight segment whose two extremities were marked on the digitized radiograph. Regarding the femoral heads, as they were not always

Fig.1 Radiological protocol. The subject stood up in a comfortable position, upper limbs resting on a support. The knees were in full extension. The subject stood on a force plate that determines the coordinates of the ground projection of the global axis of gravity (x_b and y_b). The X-ray source, the middle of the force plate and the middle of the X-ray plate were on the same alignment. The distances between the X-ray source, the force plate and the X-ray film were known and constant. By a homothetic projection, the position of the global axis of gravity was registered on the X-ray film plane (x , y)

Fig. 2A–C Spinal and pelvic geometrical model. **A** The sagittal shape of the spine was considered as a succession of curved segments representing thoracic kyphosis and lumbar lordosis (θ_1 global angle of lordosis, θ_k global angle of kyphosis) united by a straight thoracolumbar segment. Each curve was modeled by two tangent arcs of circle. The position of the global axis of gravity measured by the force plate was represented by two distances: femoral gravity offset (distance between the global axis of gravity and the middle of the femoral heads) and sacral gravity offset (distance between the global axis of gravity and the middle of the sacral plate). The pelvic parameters described by Duval-Beaupère were measured: pelvic incidence (PI), sacral slope (SS) and pelvic tilt (PT) angles. **B** The lordosis is represented by two arcs of circle tangent in the apex of the curve. The global lordosis θ_1 was the sum of the lordosis under the apex (α_1) and the lordosis over the apex (α_2). Each arc of circle is defined by its center (C) and its ray (R). **C** The kyphosis is represented by two arcs of circle tangent in the apex of the curve. The global kyphosis θ_k was the sum of the kyphosis under the apex (α_3) and the kyphosis over the apex (α_4). Each arc of circle is defined by its center (C) and its ray (R)

superposed, each center was calculated from three points on each circumference. The middle of the segment between the two head centers was considered to be the center of the femoral heads.

The position of the global axis of gravity (GAG), measured with the force plate, was projected by the software on the digitised radiograph, including the exact radiological magnification. The extent to which it was offset from the hip axis was measured.

The software reconstructs the spinal and pelvic model after the identification of a few anatomical landmarks by the operator.

Results

The mean values of the minimum, maximum and standard deviations of each variable measured are presented in Table 1.

The position of the GAG was correlated, in the horizontal projection, to the bicoxofemoral axis, called the femoral gravity offset (FGO), and to the center of the sacral end, the sacral gravity offset (SGO). The mean value of the FGO was 9 mm forward (± 12.5 mm), while the value of the SGO averaged 35.7 mm (± 15.3 mm). On a sagittal view, the GAG was positioned over the hips in 80% of the normal population. It was always in a forward position with respect to the middle of the sacral end.

The pelvic parameters studied were the pelvic incidence angle (PI), sacral slope angle (SS), and pelvic tilt angle (PT). The mean value of PI was 51.7° ($\pm 11.5^\circ$), ranging from 33° to 85° (Fig. 5A). The mean value of SS was 39.4° ($\pm 9.3^\circ$) ranging from 19.5° to 65.5° (Fig. 5B). The mean value of PT was 12.3° ($\pm 5.9^\circ$), ranging from -1° to 27.9° (Fig. 5C). The size of the pelvis averaged 123 mm (± 9 mm), ranging from 100 to 144 mm.

The studied spinal parameters were global lumbar lordosis and global thoracic kyphosis.

The mean value of global lumbar lordosis was 46.5° ($\pm 11.1^\circ$), ranging from 26° to 76° (Fig. 6) and the number of vertebral units included in the lordotic curve averaged

Fig. 3A–C Duval-Beaupère's pelvic parameters. **A** Sacral slope angle (SS), **B** pelvic tilt angle (PT), **C** pelvic incidence angle (PI)

Fig. 4 Mathematical relation between pelvic parameters: $PI = PT + SS$

Table 1 Descriptive statistical results

	Mini- mum	Maxi- mum	Mean	SD
Pelvic incidence (degrees)	33	85	51.7	11.5
Sacral slope (degrees)	19.5	65.5	39.4	9.3
Pelvic tilt (degrees)	–1	27.9	12.3	5.9
Femoral gravity offset (mm)	–24	34	9	12.5
Sacral gravity offset (mm)	8	77	36	15
Global lordosis (degrees)	26	76	46.5	11.1
Unit lordosis (degrees)	8	27.3	14.3	3.4
Global kyphosis (degrees)	25	72	47	9.2
Lordotic vertebral units	1	6	3	1
Kyphotic vertebral units	6	13	10	2

3.5 (± 1), ranging from 1 to 5.5 vertebral units. The unit lordosis, defined by the ratio between global lordosis and number of vertebral units, averaged 14.3° ($\pm 3.4^\circ$), ranging from 8° to 27.3°.

The mean value of global thoracic kyphosis was 47° ($\pm 9.2^\circ$), ranging from 25° to 72° (Fig. 6). The number of vertebral units included in the kyphotic curve averaged 9.5 (± 1.5), ranging from 6 to 13 vertebral units. The unit kyphosis, defined by the ratio between global kyphosis and number of vertebral units, averaged 5° ($\pm 1.3^\circ$), ranging from 2.4° to 8.3°.

There were no statistical differences between men and women with respect to global gravity axis position, pelvic parameters or spinal parameters.

We found a statistically significant correlation (Pearson's bilateral test) between the following values: pelvic incidence angle and sacral slope angle ($r=0.86$, $P<0.001$) (Fig. 7A), pelvic incidence angle and global lordosis ($r=0.69$, $P<0.001$) (Fig. 7B), pelvic incidence angle and pelvic tilt angle ($r=0.59$, $P<0.001$), sacral slope and global lordosis ($r=0.75$, $P<0.001$) (Fig. 7C), global lordosis and global kyphosis ($r=0.36$, $P<0.001$) (Fig. 7D), number of vertebral lordotic units and global lordosis ($r=0.56$, $P<0.001$), number of vertebral lordotic units and pelvic incidence angle ($r=0.39$, $P<0.001$), number of vertebral lordotic units and sacral slope angle ($r=0.46$, $P<0.001$), sacral gravity offset and pelvic tilt angle ($r=0.62$, $P<0.001$) (Fig. 7E).

We found no significant statistical correlation between the pelvic tilt angle and global lordosis.

Discussion

Our purpose was to perform a prospective analysis of the sagittal profile of 100 healthy young adult volunteers. At this age, the growth period is over, but there is no aging damage. We did not find any differences between men and women. We chose to use a radiographical analysis for its precision, in preference to surface topography analysis,

Fig. 5A–C Pelvic parameters distribution in the studied population. **A** Pelvic incidence angle, **B** sacral slope angle, and **C** pelvic tilt angle

Fig. 6 Spinal parameters (lordosis and kyphosis) distribution in the studied population

which cannot provide the real shape of the spine or pelvis, the lumbar lordosis being diminished by the spinous processes or increased by the glutei or a horizontal sacrum [15]. Each radiograph was done the same way, with the upper limbs in the same position, inducing the same effect on the shape of the spine. By this method, we were able to make comparisons between subjects. The software can identify precisely the centers of the femoral heads, the upper sacral end for the pelvic shape, and the anterior body line for the spine shape.

Axis of gravity

Our method of measurement makes it possible to obtain simultaneously the individual position of the global axis

of gravity and the radiograph, keeping the subject in the same position. The risk of error is thus minimal, as the operator simply has to read the values of the coordinates of the GAG and register them on the lateral radiograph with the computer. This is a dynamic position, independent of anatomical parameters, unlike the classic sagittal vertical axis [19]. By a method of barycentrometry, Duval-Beaupère defined the position of the center of gravity of the upper part of the body over the sacrum at the level of T9 with a projection on the center of the sacral end [5]. We prefer to use the GAG, because it takes into account the lower limbs, and because the body does not finish at the sacrum. We correlated the position of the GAG with the bicoxofemoral axis, because of the possible regulation of the sagittal balance by rotation of the pelvis around it, like

Fig. 7A–E Main statistical linear correlations (Pearson's bilateral test). **A** Correlation between pelvic incidence angle and sacral slope angle ($r=0.86$, $P<0.001$), **B** correlation between pelvic incidence angle and global lordosis ($r=0.69$, $P<0.001$), **C** correlation between sacral slope angle and lordosis ($r=0.75$, $P<0.001$), **D** correlation between global lordosis and global kyphosis ($r=0.36$, $P<0.001$), **E** correlation between sacral gravity offset and pelvic tilt ($r=0.62$, $P<0.001$)

a reverse pendulum [16]. When the pelvis is tilted posteriorly, the sacral end is projected behind, displacing the axis of gravity in the same direction. This was well demonstrated by the position of the GAG with respect to the femoral heads, 73% of the cases having the GAG positioned 20 mm anterior or posterior to the bicoxofemoral axis, with an average position of 0.9 mm anterior. Regarding the sacrum, the GAG was always positioned anterior to the sacral end. Regarding the spinopelvic parameters, the main correlation was obtained with the pelvic tilt angle, which demonstrated the effect of rotation of the pelvis around the hips on the regulation of the GAG position.

Pelvic parameters

If we consider the pelvis as a pelvic vertebra, as suggested by Dubousset [4], we have to define a relationship between the unit spine-sacrum (sacral end) and the unit pelvis-lower limbs (hip joints). This is the reason why we used the pelvic incidence angle defined by Duval-Beaupère. This is an anatomical signature, specific for each individual.

There are some drawbacks regarding measurement of the pelvic points – the sacral end and centers of femoral heads. In this study, we never found any difficulty in identifying the sacral end, because there were no anatomical changes of the lumbo-sacral junction. In some infrequent

cases, not encountered in our study, it is not possible to measure the incidence angle (as with a dome-shaped sacral end in spondylolisthesis), or to correlate the value (as with lumbo-sacral anomalies).

Due to the obliquity of the radiographs in the pelvic area on long films, it is almost impossible to obtain the superposition of the two femoral heads. This was the reason why we used the middle of the line between the two head centers. If the radiographs are taken in a true lateral position, the superposition of the heads is vertical and the range of error in calculating the angle of pelvic incidence is low. If the pelvis is rotated, the superposition of the femoral heads is horizontal; the range of error then becomes much more important and the radiograph is not acceptable. We found the same range of values as reported in other series [13, 14], ranging from 35° to 85°, with a mean value of 51°. Even if there is a peak incidence at 50°, the distribution of the data is not really Gaussian, with a lot of cases in the field of low-grade incidence (34% <45°). For one individual, the constant value of the incidence angle is linked to two positional parameters – the pelvic tilt and the sacral slope – by the relation $PI=PT+SS$ (Fig. 4). In this way, the range of values of the positional pelvic parameters is determined by the value of the incidence angle. If we compare the values of SS or PT with PI, we have a good correlation between the incidence and the sacral slope, which increases proportionally with the incidence, with a range of 46° (19.5° to 65.5°). This is not as well demonstrated for the pelvic tilt, which has a low correlation with the incidence (0.59) and a range of 29° (–1.0° to 27.9°). This may be explained by the fact that we were analyzing normal persons with a well-balanced spine. Under these conditions, the regulation by pelvic tilt was limited, but adapted to the position of the GAG. The measure of the pelvic parameters is dependent on the position of the lower limbs. The pelvic parameters are measured in the pelvic system, with the center of the bifemoral axis as zero-point. But the femoro-pelvic system oscillates through the knees axis. Mangione and Senegas describe a femoro-pelvic angle between the proximal femoral shaft direction and the line between the center of the femoral heads and the center of the sacral end [14]. The pelvic tilt is dependent on the femoro-pelvic angle (FP) and on the angle of flexion of the knees. If the knees are in straight extension, $PT+FP=180^\circ$, the position of the pelvis is then well defined by the pelvic tilt angle. But if the knees are in flexion, the effect of pelvic tilting is increased, while if the knees are in recurvatum, the pelvic tilting is decreased. To avoid this positional effect of the knees on the pelvic position, all the X-rays were done with the knees in extension.

Spinal parameters

The sagittal shape of the spine was described from the sacral end to T1 on the anterior body line. The software

allows a geometrical description of the spine with simple curves (arcs of circle) and tangential lines. Each curve, lordosis or kyphosis, is mathematically identified by one global angle and by the number of vertebral units included in the curve. By this way, we can calculate a vertebral unit angle whose mean value was 5° for kyphosis and 14.3° for lordosis. We think that this angle is the best way to determine the quality of a curve, allowing us to speak of hyper- or hypocurvature when the vertebral unit angle is greater or smaller than its mean value. For a similar global angle, a two-units lumbar lordosis is mechanically worse than a four-units curve. There is a correlation ($r=0.36$, $P<0.001$) between lumbar lordosis and thoracic kyphosis; Jackson and McManus [9] also found a significant correlation ($r=0.5$, $P<0.0005$) between kyphosis and lordosis. The stronger correlation is due to the fact that in this last study, the spine was divided in two parts, with a Cobb measure for each part.

The relation between lumbar lordosis and sacral slope has already been well described by Stagnara [17]: lumbar lordosis increases linearly with sacral slope. We confirm this relation with the strongest correlation found in our study ($r=0.86$, $P<0.001$). Duval-Beaupère demonstrated that there is a relation between the pelvic incidence angle and lumbar lordosis. We found the same correlation ($r=0.7$, $P<0.001$). The greater the incidence angle, the greater the values of lumbar lordosis. This is, however, only partially true: as there is a correlation between the thoracic kyphosis and lumbar lordosis, the lumbar lordosis is a compromise between the shape of the thoracic spine, the shape of the pelvis and the pelvic position. In other words, for a same value of pelvic incidence, we have found different shapes of spine and different positions of the pelvis. There is an interaction between these variable parameters.

Based on these findings, we propose a scheme of organisation for the sagittal balance of the standing human body. The incidence angle is constant and cannot be changed by any parameter. We have seen that the best correlation was between pelvic incidence and sacral slope, and that the direction of the action had to be PI on SS. Therefore, the first step of this scheme is that the pelvic incidence angle acts directly and solely on the sacral slope angle. From top to bottom, the variable parameters are: thoracic kyphosis, lumbar lordosis, sacral slope, pelvic tilt, knees position. The sacral slope is balanced by the incidence angle, the sacral slope balances the lumbar lordosis and the pelvic tilt, which in turn balance themselves with thoracic kyphosis and knees position. Reciprocally, the lower limbs act on the pelvic tilt, which balances the sacral slope and the lumbar lordosis, or the thoracic kyphosis can balance the lumbar lordosis which can balance the sacral slope and so on. This explains that the further we are from the sacral slope, the smaller the correlation with the incidence angle, because of the interdependence of the variable parameters. All the variable parameters balance themselves, by muscular activity, in order to

maintain the global axis of gravity on the femoral heads. In low-grade pelvic incidence, the range of adaptation of the variable parameters is small due to the limits of the sacral slope. In high-grade pelvic incidence, the range of adaptation of the variables is large. With the help of this theory, we can explain how the sagittal balance can be disturbed in various pathologies. If one of the variable parameters is pathologic, it becomes a fixed variable outside of its normal limits. In such a case, it acts directly on its neighbor parameters, in only one direction. Consequently, all the variable parameters have to adapt themselves to the locked parameter, within the limits set by the pelvic incidence.

Conclusion

Spinopelvic sagittal balance with normal persons is a combination between spinal and pelvic shape parameters. The pelvic shape, quantified by the incidence angle, de-

termines the position of the sacral end. The spinal shape varies, from flat to curved backs. Generally the spinal shape is adapted to the pelvic shape, the quantity of lordosis growing with the sacral slope, providing a good combination between the spine and the pelvis. But in some cases, this combination is not correct, and there are curved spines with low-grade incidence and flat spines with high-grade incidence. These combinations are not mechanically efficient, and this could be a way to explain a postural evolution to low back pain. Further studies comparing the database of this normal population with pathologic populations with spinal disorders would allow the determination of whether there are better pelvic shapes and better combinations between spine and pelvis for an optimal sagittal balance, and if low back pain could be mechanically explained in this way.

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