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A Barycentremetric Study of the Sagittal Shape of Spine and Pelvis: The Conditions Required for an Economic Standing Position

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The standing posture of 17 young men and women were studied using Barycentremeter measurements and full spine radiograph with a single referential system. These procedures provide in vivo measurements of the weight and center of weight supported by each vertebra and the coxofemoral joints. The relationship between the vertebra, the sacrum or the coxofemoral rotation axis and the center of weight they support, is displayed. The moment of the corresponding force may also be assessed. Mean values were computed and the relation with spine sagittal curves and pelvic parameters were studied. The position of the center of weight, in front of or behind the vertebra or the coxofemoral joints, requires an opposing muscle force to ensure mechanical stability. The load exerted on the vertebra cannot be precisely evaluated, but we can describe the way in which these loads vary when the spinal curves and the pelvic slope change. This study provides basic data suggesting that there is a tendency to maintain the body in the most economical position in terms of muscle fatigue and vertebral strain. Individual anatomical shapes and pelvic parameters of the pelvis induce corresponding specific sagittal curves of the spine. This concept is very useful for analysing pathological situations and devising appropriate treatment.

Keywords—*Spine, Pelvis, Morphology, Gravitational parameters, Posture.*

INTRODUCTION

Several human postures have been described by anatomists, such as Staffels (22), Delmas (5,6), and Bonne (2). However, these are clinical morphological descriptions, with little or no anatomical foundation. There remains a need to take into account the three-dimensional components of the spine in studies on spinal pain or deformity, that underline the lack of anatomical criteria for normal posture. Stagnara *et al.* (23) have provided an approach to references for kyphosis, lordosis, and sacral slope and point out good correlation between lordosis and sacral slope. Vidal *et al.* (25) suggested a classification in terms of pelvis stability and the "antero-posterior spine axis."

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They referred to the center of gravity line, but were unable to measure this parameter. During *et al.* (8) studied the postural characteristics of the lower back system, lumbar lordosis, and pelvic parameters. They were able to obtain line of gravity parameters with a platform of force transducers. They concluded that sacral declivity and the lordotic curve were mutually interdependent in order to maintain postural equilibrium. They emphasized that the line of gravity, can be a doubtful parameter because of the influence of the lower part of the body on its registration.

Biomechanical studies of human posture must take into account not only the physical interrelation of the skeletal elements, but also the gravitational and antigravitational forces exerted upon them. The study of spinal posture requires knowledge of the weight and the center of weight supported by the sacrum and the coxofemoral joints. While the center of gravity is fixed for a rigid body, its position changes for an articulated one, so that the center of gravity must include a parameter defining the relative position of all articulations. King Liu *et al.* (16) used body slices from a human cadaver to obtain such data. They employed compound pendulum techniques to calculate the inertial properties of body slices forming a unit with each vertebra.

The Barycentremeter, a gamma ray scanner (Fig. 1), provides *in vivo* measurement of the weight and center of weight of successive body slices from the top of the head to the coxofemoral joints (9,18). This method of measuring the mass and the coordinates of its center in biological systems measurements, its application in measuring the mass of human body segments *in vivo* and in locating their centers, together with the validity of such measurements have been described and published previously (12,18). The basic data are used to calculate the weight and the center of weight of body slices equivalent to the height of each vertebra by using a common coordinate

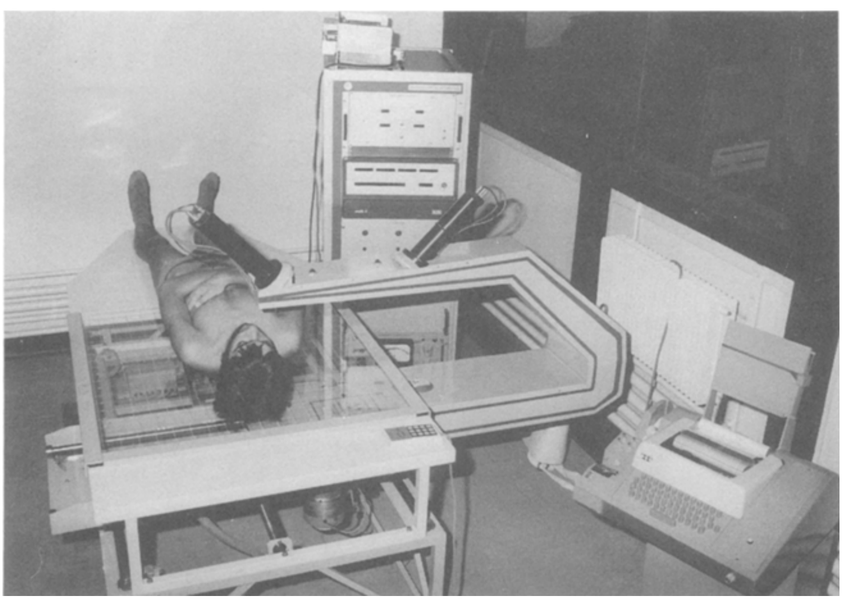


FIGURE 1. The Barycentremetre table.

system for the gamma ray scanner and the X-ray system of two orthogonal full-spine radiograms (Fig. 2) (10,13). It is assumed that the relationship between the body-slice center of mass and its vertebra does not change, although the coordinates of the slice and of its vertebra change when the subject moves from the supine to a standing or sitting position (4,11). Thus this constant relationship between the vertebra and its interdependent body-slice center may be transferred from the supine radiograph to the sitting or standing one. These new data can be used to compute the weight and center of weight supported by each vertebra and by the coxofemoral joints for each position (3). These successive centers are represented by the successive points as shown in Fig. 3. The lever arm of the corresponding force may also be assessed. It is indicated by a cross, in Fig. 4, which is the vertical projection, in front of the vertebra or the coxofemoral joints, of the center of weight supported by the corresponding level. The relationship between the vertebrae, the sacral or the bicoxofemoral axis and the center of weight they support may thus be displayed, as well as the lever arm of the corresponding force for each corresponding position.

The position of the center of weight, in front or behind the vertebra or the coxofemoral joint, requires an opposing muscle force to ensure stability of the mechanical system. Therefore, although we cannot precisely evaluate the load exerted by all the weight and stabilizing forces, we can evaluate the way in which this load varies when the anatomical relationship of the center of weight changes following alterations in the spinal curves and pelvic tilt (3).

Using this method, we have studied the center of weight supported by the coxofemoral joints (GF), its anatomical connections with the thoracic vertebra (GFT) in standing position and those of its vertical projection with the sacral plate (GFSP) and the bicoxofemoral axis (GFFP) (Fig. 5).

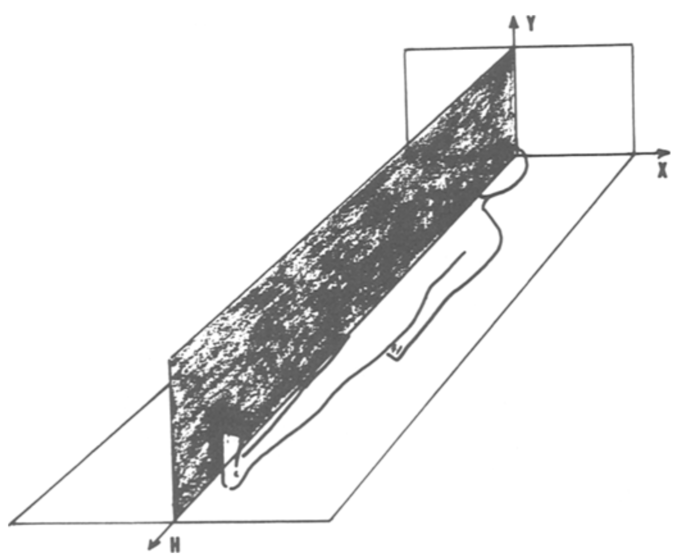


FIGURE 2. The coordinate system.

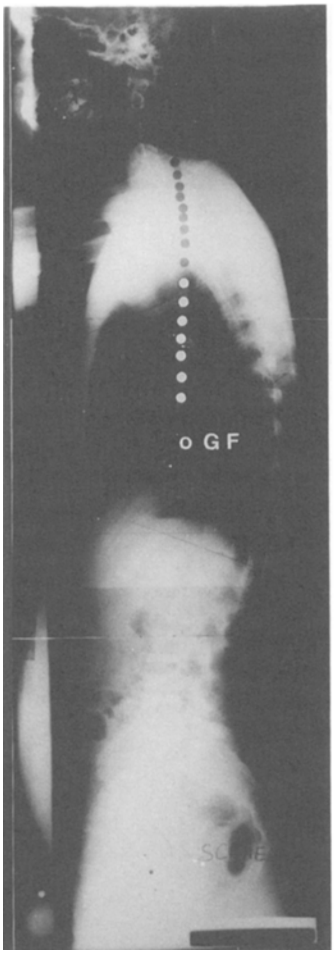


FIGURE 3. The centers of weight supported by successive vertebrae.

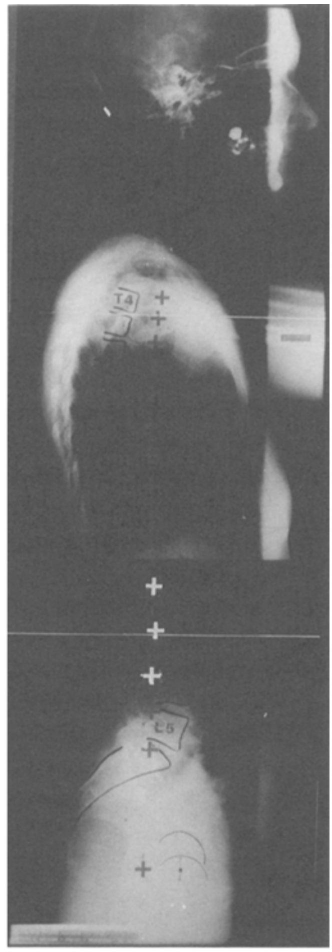


FIGURE 4. The vertical projection of the center of the weight supported by each anatomical level in front or behind the corresponding vertébra or the coxofémoral joints.

MATERIAL AND METHOD

The standing postures of 11 young men (mean age 29.7 years, SD 12, mean weight 71.2 Kg, SD 7.3, and mean weight 71.2 Kg SD 7.3) and 6 women (mean age 29 years, SD 10), mean weight 55.3 Kg, SD 4.8, and mean height 166.8 cm, SD 4.6) were studied. X rays were taken using the standard protocol for standing view, with a 2-meter focus. None of these subjects had any frontal spine deformity and their centers of weight were strictly in the median sagittal anatomic plane. Consequently, only their own sagittal radiographs could be used.

We first evaluated the similarities between the individuals and computed mean values of GFT, GFSP, GFFP. These data were used to examine the causes of variations between them using the anatomical parameters of the spine and pelvis.

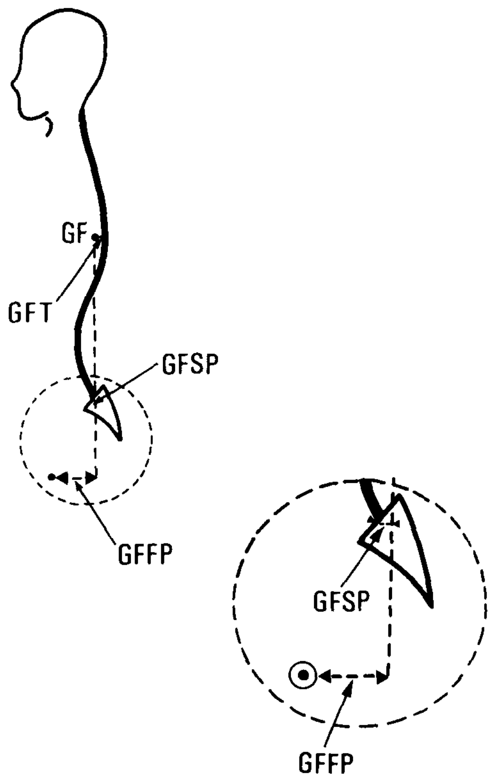


FIGURE 5. The gravitational parameters referred to in the study.

The anatomical parameters were:

1. For the spine: degrees of kyphosis and lordosis curves, measured by the Cobb technique, between T4, T12 and S1. They are variable, individual parameters.
2. For the pelvis (Fig. 6): five parameters were measured on the sagittal X-ray view. Two are specific to the anatomical morphology of the pelvis; they are constant, individual parameters.
   - The *incidence* is the complement angle (β) between the upper plate of S1, the axis running through the middle of the upper sacral plate, and the bicoxofemoral axis.
   - The *thickness* (SF) is the length of the segment linking the middle part of the sacral plate and the bicoxofemoral axis.

   The other three are dependent on the anatomical morphology and the spatial orientation of the pelvis at any given time. They are variable, individual parameters.
   - The sacral slope, measured by the angle (α) between the upper sacral plate with the horizontal.
   - The *porte à faux* or *overhang*, is the geometrical range between the middle of the sacral plate and the intercoxofemoral axis, measured in millimeters.

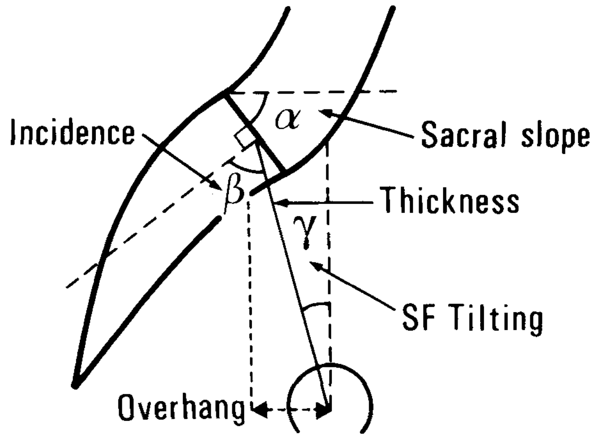


FIGURE 6. The pelvic parameters studied.

It is positive when the hips are in front of the sacral plate and negative when the hips are behind it.

- The *SF Tilting* (γ) is the angle between SF and a vertical line crossing the interfemoral axis, it reflects the spatial tilting of the pelvis. SF tilting is positive when the hip is in front of the sacral plate and negative when it is behind it.

The data from the radiographs were collected using a high resolution ultrasonic digitizing tablet placed over the X-ray plate reader. All calculations were performed on an Atari microcomputer.

RESULTS

Mean Values

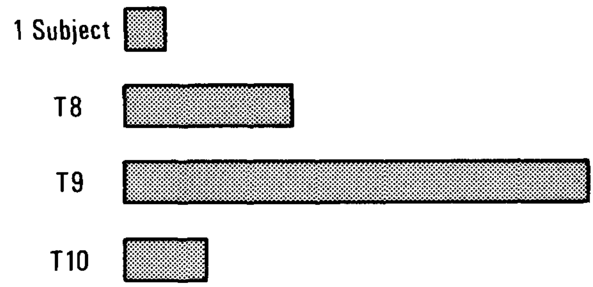
Gravity Parameters. The center of weight supported by the coxofemoral joint, GF, was generally, in front of T9, range T8 to T10, as shown on the histogram of this level (Table 1). It was in front (positive value) of the anterior side of the vertebra, measured on the lateral x-ray view. The mean distance (GFT) is 15.5 m, SD 10.9, range 0 to 31.

The vertical projection of this center of weight (GFSP) crossed the upper sacral plate behind its middle part (positive values), mean 14 mm, SD 10.3, range 4 mm in front to 25 mm behind. This projection lay behind the bicoxofemoral axis (GFFP), mean 35.07 mm, SD 10.87, range 17 to 60 mm behind.

Anatomical Factors. Spinal parameters: The mean thoracic kyphosis was 34.3°, SD 8.46, range 20 to 52°. The mean lumbar lordosis was 59.8°, SD 9.7, range 42 to 77°.

Pelvis parameters: The mean value of sacral slope was 40.9°, SD 7.0, range 30 to 53. The mean value of incidence was 51.8°, SD 9.4, range 40 to 65. Incidence was not stature or sex dependent. The mean value of thickness (SF) was 120 mm, SD 7.5 mm, range 107 to 136 mm. Thickness was not stature or sex dependent. The mean value of overhang was +20.31 mm, SD 13.20, range −7 to +43 mm. The mean value of SF Tilting was +10.7°, SD 5.9, range −1 to +24.

TABLE 1. Histogram of GF level (center of the weight supported by the coxofemoral joints)



Causes of the Individual Variations in the Vertical Projection of the Center of Weight Behind the Coxofemoral Joint

Regression coefficients and partial regression coefficients between the different parameters were computed. All parameters indicated lack of a direct relation with GFSP on the one hand and with thickness on the other. Consequently, these two parameters were not used in any subsequent analysis. Many correlations between the other parameters were significant (Fig. 7). Partial correlation indicated a single range of interrelations between these factors:

- GFFP is directly correlated only with overhang ($r = .730$, S***, $p < 0.001$).
- Overhang is directly correlated with SF Tilting ($r = .795$, S***, $p < 0.001$).
- SF Tilting is directly correlated with the incidence ($r = .619$, S***, $p < 0.001$).
- The incidence is directly correlated with the sacral slope ($r = .795$, S***, $p < 0.001$).
- The sacral slope is correlated with the lumbar lordosis ($r = .873$, S***, $p < 0.001$).
- The lumbar lordosis is correlated with thoracis kyphosis ($r = .589$, S**, $p < 0.01$).

The degree of thoracic kyphosis induces the variable position of GF ahead of the vertebra ($r = .812$, S***, $p < 0.001$): the distance varied from 0 to 14 mm in front of the vertebra for a kyphosis of less than 35° and from 20 to 32 mm in front of the vertebra for a kyphosis of more than 35°.

DISCUSSION AND CONCLUSION

The methodology, the accuracy of the measurements made with the barycentremeter, and the validity of determining the anatomical connections of the centers of weight have all been discussed previously (9,12,13,18).

This discussion is limited to the methodology used to measure the pelvic parameters and the influence of a more or less true sagittal radiographic view of the spine and pelvis on these values.

The bicoxofemoral axis was obtained from the middle point of the segment connecting the centers of the two femoral heads. In these conditions, all the pelvic ana-

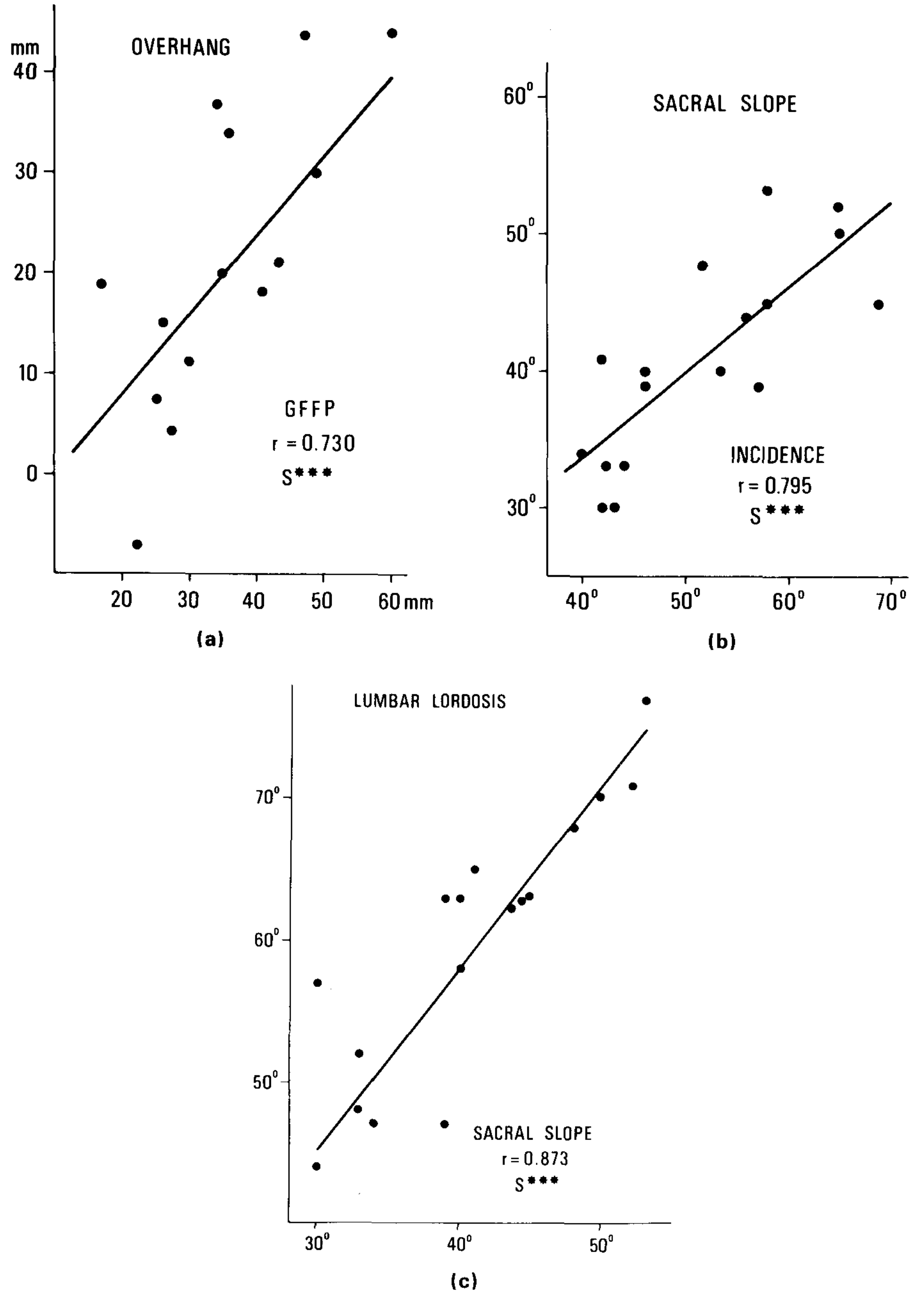


FIGURE 7. Some of the most significant correlations. Probability: * = 0.05, ** = 0.01, * = 0.001.**

tomical points used to measure the defined anatomical parameters were on the same vertical sagittal plane crossing the middle of the frontal plane. Thus, all these parameters were equally reduced when the sagittal view was not strictly true. Then only the mean values of the parameters risk being slightly reduced but the precision of the regression coefficients is unaltered. The accuracy and reliability of measurements of the anatomical parameters, especially the incidence since this parameter seems to be important, must be assessed. On a single radiograph, incidence is measured with an accuracy of 1 to 2°, and the value varied by less than 3° when measured on several radiographs in the supine or standing positions for the same patient. The range of values increased to a maximum of 6°, in a few subjects, if measurements were also made in the sitting position. This increase in the range of values may indicate slight mobility of the sacroiliac joint when going from the supine or standing positions to the sitting position. In our first experiments, the value of incidence seemed to be stable during growth. The mean value of this parameter measured on this small sample is in good agreement with those (mean 51.7°) of another sample of 187 subjects studied by our Reseau de Recherche Clinique INSERM.* The mean complementary angle of incidence measured by During (8) was 41.27 for 52 subjects.

The mean spine parameters are in agreement with those of Stagnara (23). The mean sacral slope values are similar to those of both Stagnara *et al.* (23) and During *et al.* (8). Both of these publications emphasize the very close correlation between sacral slope and lumbar lordosis. Our data, as well as those of Stagnara *et al.* (23), indicate a significant but very close correlation between lumbar lordosis and thoracic kyphosis.

The localization of weight forces slightly behind the femoral head may explain the observation of Joseph in 1954 (15,16) of a lack of muscular action potential in hip extensor muscles in the standing posture, an observation which was surprising at that time. No posterior stabilizing forces are required in such conditions. These results suggest that there is a tendency to maintain the most economical position of the body, in terms of muscle fatigue and skeletal strain. We have checked this lack of muscular action potential on the biceps femoris and gluteus maximus of four subjects, in the standing position. The biceps femoris shows action potentials when the trunk is tilted forward, moving the center of weight to 30 mm in front of the bicoxofemoral axis sagittal coordinate (Fig. 8). For a GF projection from 30 mm behind to 30 mm in front of the coxofemoral joint suggests that it is possible that frictional forces in the hip joints ensure stability without active muscular contraction.

Therefore two parameters play an important part in such an economic standing posture: the overhang whose sufficient size provides an economic standing posture, and the incidence, the single constant parameter whose varying size helps more or less to stabilize the pelvis above the coxofemoral joints.

A simple geometrical demonstration proves that the sacral slope + SF tilting = incidence, and the parameters in this study provide evidence of this relationship.

These results suggest that the stability runs from the ground up to the thorax, and that the incidence, the only individual constant parameter, plays an important part in the changes in the sagittal curves of the spine from one individual to another, for a given pelvic tilting, to provide the most economical equilibrium.

Positive tilting contributes to an economical standing posture; it requires good extensibility of the hip flexor muscles. Lack of extensibility of these muscles produced decreased tilting and increased sacral slope. Lumbar lordosis is increased when tilting is negative, as sacral slope = incidence + tilting.

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*"Reseau de recherche clinique INSERM n° 850011" members: J. Dubousset, H. Graf, J. Hecquet, B. Mouillesseaux and G. Duval-Beaupère.

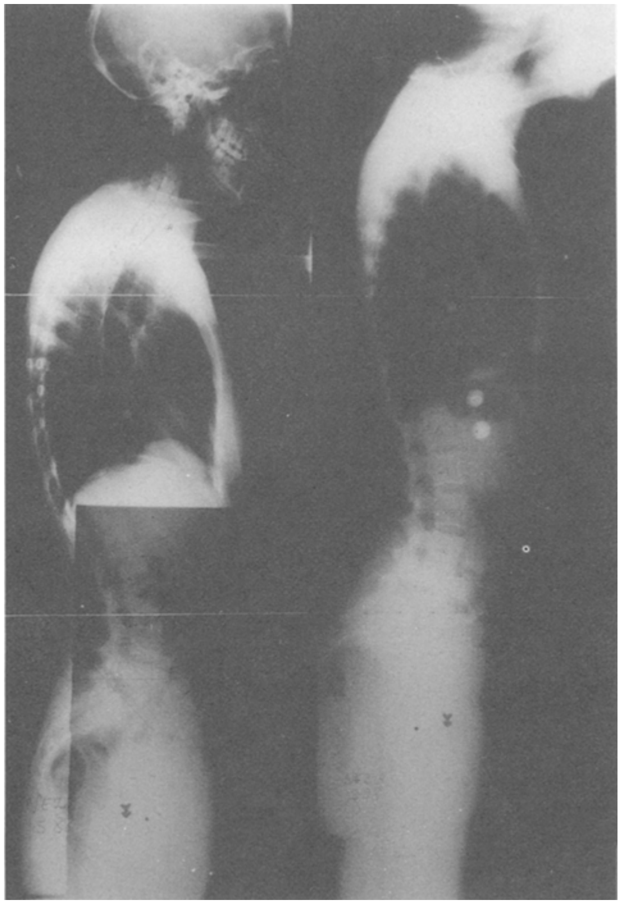

FIGURE 8. GFFP in normal standing posture (left) and in forward bending of the spine when biceps femoris muscular action potential occurred (right).

The least flexor motion of the hips when incidence is less than 40° may induce negative tilting. A small incidence also induces a shorter lever arm of the hip extensor muscles. Consequently, low values of incidence decrease the chances of an economic standing posture. We had observed in our clinical practice that subjects with small incidence values are more liable to develop hip flexor contractures. We have also found that there are constant action potentials of gluteus maximus and ischiojambier muscles in these patients in the standing position. One of these subjects frequently adopted a flexed knee position, because it was more restful. Full spine standing sagittal radiographs of this subject in knee extension and in his usual attitude of knee flexion were taken and the center of weight were computed for the two attitudes (Fig. 9). The vertical projection of GF (GFFP), in front of the bicoxofemoral axis when the hips were extended, and behind when they were flexed, corroborate the patient's choice of position.

An economic standing position does not depend on the pelvis alone, but requires

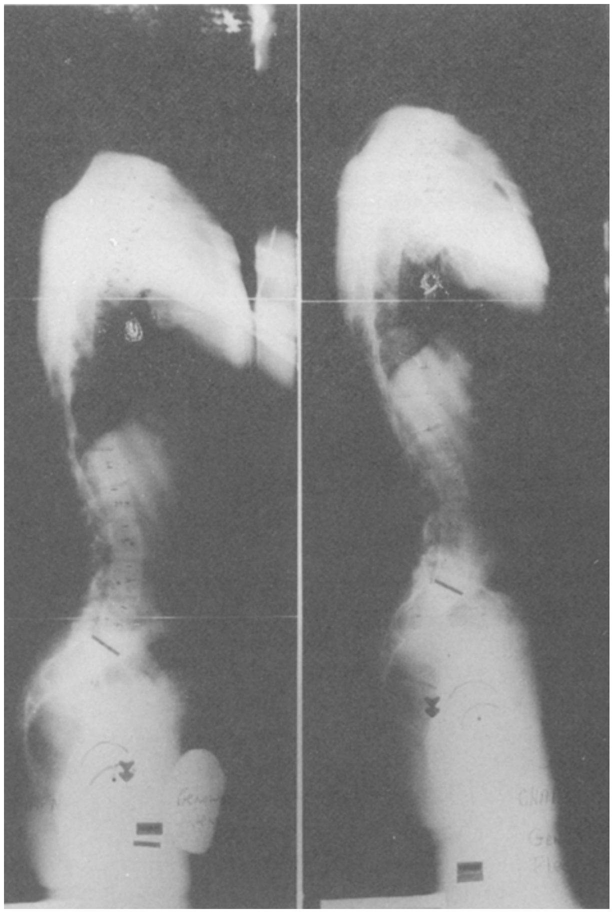

FIGURE 9. Subject with an incidence less than 40°, restful standing posture with hip flexed to the right, and unrestful posture with hip extended to the left.

specific spine sagittal curves, especially lumbar lordosis curves, which correctly fit the sacral slope. This concept is supported by the strong correlation between the sacral slope and lumbar lordosis, and the lesser correlation between thoracic kyphosis and lumbar lordosis. In these conditions, an inappropriate lumbar lordosis, which is too small induces forward displacement of the weight forces, which then tend to fall in front of the bicoxofemoral axis, and hence to induce an uneconomic standing position.

Such findings must be taken into account in determining the biomechanical factors involved in the progression of spinal deformities and especially in scoliosis. The sagittal situation of the weight forces especially when they are in front of the vertebra and of the coxofemoral joints (because of the stabilizing forces they require) are no less important than the frontal situation of these forces, laterally distant from the curve apex. The barycentremeter provides a method of studying this three-dimensional geometry.

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