REVIEW ARTICLE

Hip–spine relations and sagittal balance clinical consequences

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Abstract

Introduction The role of the pelvic area in sagittal balance is evident for spinal surgeons, but the influence of the coxofemoral joint is underestimated and inadequately explained by conventional imagery. Comprehensive analysis of the pelvic and subpelvic sectors as part of the sagittal, frontal and cross-sectional balance of the trunk sheds new light on some spinal diseases and their relation to the pelvis.

Methods This analysis, based on innovative radiologic methods as the EOS® technology but also on a new look at conventional imaging makes it possible to better analyze standing lateral images and seated images.

Results Disturbances can come from atypical morphotypes or from unusual postures as in aging spine. The measurement of available extension and the concept of available flexion provide new information regarding individual's adaptation to the imbalance induced by disorders of the spine or lower limbs.

Conclusion A comprehensive assessment of each patient and in particular of the complex comprising the spine and the pelvis, is essential for understanding each individual's adaptation to the imbalance induced by disorders of the spine or lower limbs.

Introduction

Trunk balance is the manifestation of a postural strategy conditioned by anatomic and functional characteristics, sometimes very different from one person to another. Degeneration of this steady state, often associated with spinal aging, can generate a cascade of functional, neurological, and mechanical events. The role of the pelvic area in sagittal balance is evident for spinal surgeons, who consider sacral slope, pelvic incidence, and pelvic tilt in their planning and analyses [1–6]. On the other hand, the influence of the coxofemoral joint is underestimated and inadequately explained by conventional imagery. These anatomic and functional considerations often remain foreign to hip surgeons, who focus on the bone landmarks of the pelvis for their navigation, individualized adjustments, and failure analyses. The AP or frontal image of the pelvis is the "gold standard"; a lateral view of the pelvic area is rarely used. Influenced by the classic anatomic culture of cross-sectional slices, they consider the CT scan as a reference tool for the "horizontal" assessment of the coxofemoral joints [5–10].

Our objective is to call attention to a broader view of the pelvic and subpelvic regions as part of the sagittal, AP and transversal balance of the trunk. This analysis, based on innovative radiologic methods as the EOS® technology but also on an original approach of conventional imaging makes it possible to look with new eyes at numerous aspects of diseases of the hip and spine, from the perspective of a real functional entity.

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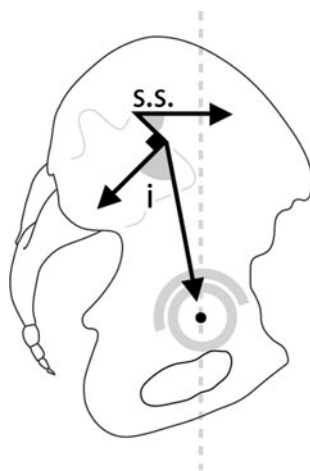Assistance Publique-Hôpitaux de Paris, Paris, France

Fundamental principles: postural variations of the lumbopelvic bone markers in the sagittal plane

Each subject is characterized by a "morphologic" parameter: the angle of incidence, which schematically represents pelvic thickness. The adaptation of other functional factors, such as pelvic tilt, and the spinal parameters (sacral slope, lumbar lordosis, and thoracic kyphosis) makes it possible to position the center of gravity of the trunk specifically so that it is supported by the femoral heads relative to the pelvic base, to maintain balance with only a minimal muscular effort [11–13] (Fig. 1).
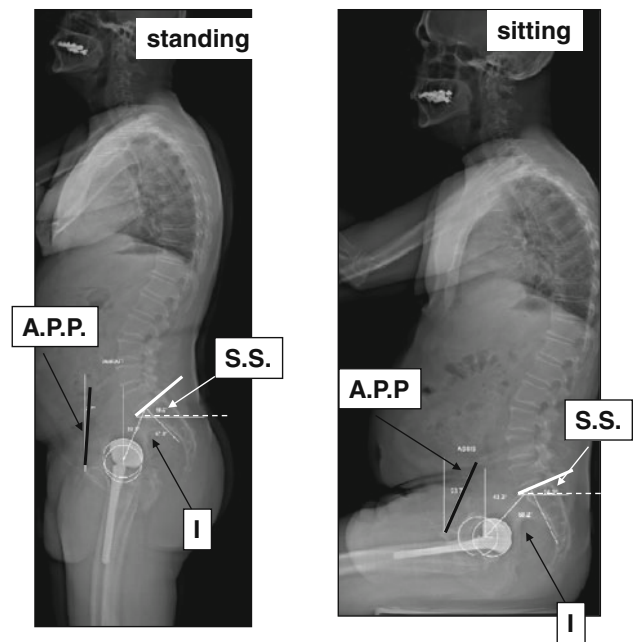
The pelvis moves, rotating around the bicoxofemoral axis, leading to both anterior tilt (where the upper portion of the pelvis tips forward) and posterior tilt (upper portion of the pelvis tips backward). The variations in the angles of the sacral slope determine the range of this pelvic tilt, and its variations in turn influence the orientation of the anterior pelvic plane or the Lewinnek plane classically used as a reference for navigation of the acetabular components in total hip arthroplasties (THA) (Fig. 2) [14]. The surprising consequences of some spinal arthrodesis or stiffening on the hips and the difficulties of adjusting prostheses below stiffened spines illustrate the importance of these anatomic-functional parameters.

The standing position (Fig. 3) corresponds to a forward tilt of the pelvis as a whole. In this situation, the upper plate of S1, viewed laterally, makes an angle of approximately 35 to 45° between the sacral slope and the horizontal [15, 16]. Some subjects have a small sacral slope angle in standing position: we talk then about posterior pelvic tilt (or pelvic retroversion or pelvic extension), and the sacrum seen on a lateral image appears more vertical than usual (Fig. 4).

On the contrary, other subjects have a very horizontal sacrum in standing position with a sacral slope angle

Fig. 2 EOS® views of the sagittal balance of a patient with a THA, in standing and seated positions. The incidence does not change regardless of position. The sacral slope is higher in a standing than a seated position. Simultaneous variations of the inclination of Lewinnek's plane (the posterior tilt of this plane is associated with the posterior pelvic tilt in a seated position). *I* incidence, *SS* sacral slope, *APP* angle between the Lewinnek plane and the vertical plane
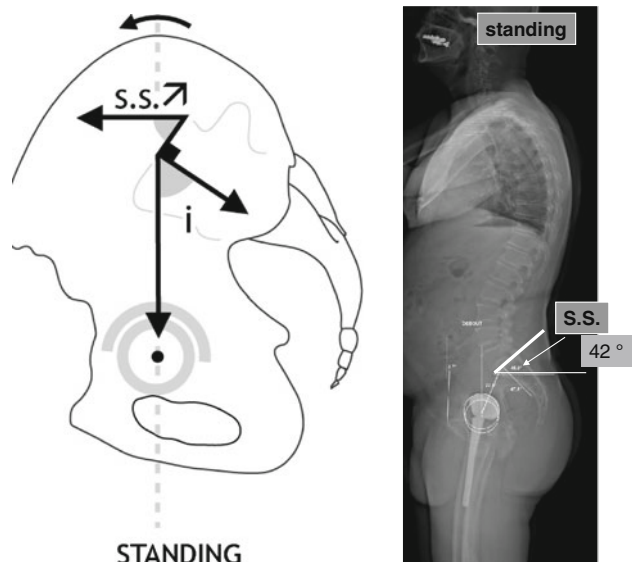

Fig. 3 Diagram of the standing position: anterior tilt (flexion) of the pelvis with horizontalization of the sacrum and increase of the sacral slope. The incidence is invariable and does not change

sometimes much greater than 50° (anterior pelvic tilt or pelvic anteversion or pelvic flexion) (Fig. 5).

In the supine position, when the lower limbs are extended, the sacral slope is often greater than in standing position. The measurement of its angle with the vertical

Fig. 1 Definition of the pelvic incidence (morphologic parameter invariant for a given subject, with a mean value of 50–55°) and of the sacral slope (functional parameter that varies according to position)

Fig. 4 Permanent posterior pelvic tilt and imbalance of a spine stiffened by a long arthrodesis. The sacral slope is low in both the standing and seated positions. In standing position, the pelvis and the spine function as if the patient were in a seated position
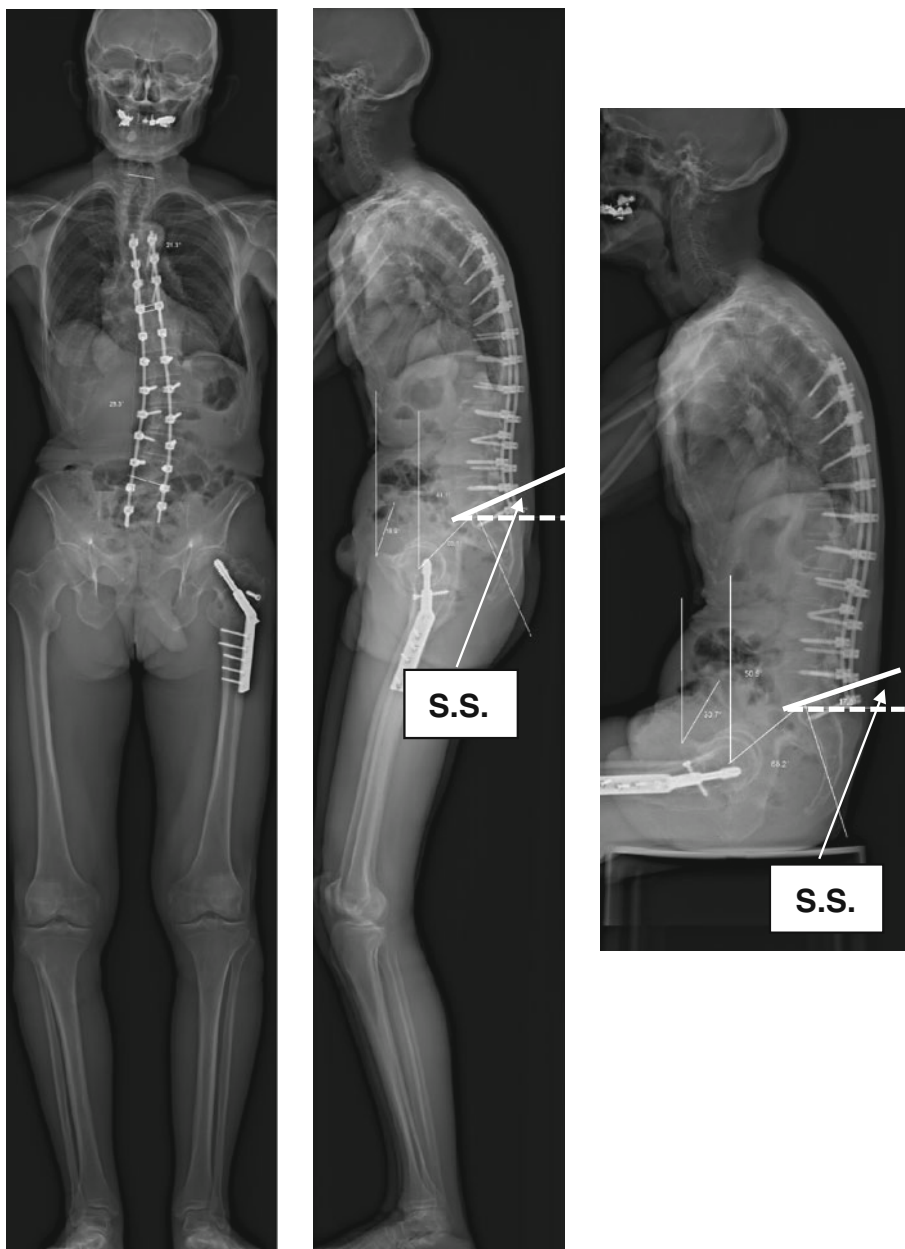
often exceeds 45° [17, 18]. This can be seen on scout views of pelvic CT scan. This additional pelvic tilt may not be well tolerated in the case of a stiff or deformed spine since the dorsal decubitus position deepens lumbar lordosis. Sometimes a limitation of the available extension of the hips or posterior osteoarthritis make a strict decubitus position unbearable, at least without a slight compromise flexion of the coxofemoral joints.

In a sitting position, the phenomenon is inversed (Fig. 6). The pelvis tilts backwards as it progresses toward a sitting position. The sacral slope diminishes, to values of 20 to 25° on average [15, 17]. This slope may still be slightly positive (by 5–10°) or even sometimes negative. As a function of the height of the seat, the subject's

morphology or any associated spinal disease, we observe pelvic posterior tilt (pelvic retroversion or pelvic extension) more or less accentuated with a sacrum more or less vertical. The difference in the values of the sacral slope between standing and seated positions makes it possible to define the available flexion associated with the lumbosacral joint (extrinsic available pelvic flexion) by opposition to the potential for flexion associated with the coxofemoral joint (intrinsic available pelvic flexion).

Progression from standing to sitting positions causes considerable modification in the orientation of the anterior pelvic plane, today considered the reference for adjusting the acetabular cups [19–21]. These variations must concern us. Lewinnek's plane (anterior pelvic plane) is evaluated in

Fig. 5 Patient with an exaggerated anterior pelvic tilt: the sacrum is very horizontal in standing position with a sacral slope greater than normal

standing

S.S.

sitting

S.S.

sitting

S.S.

24 °
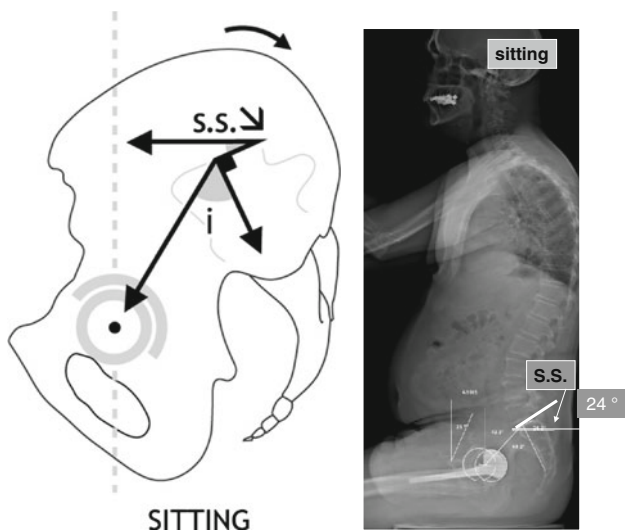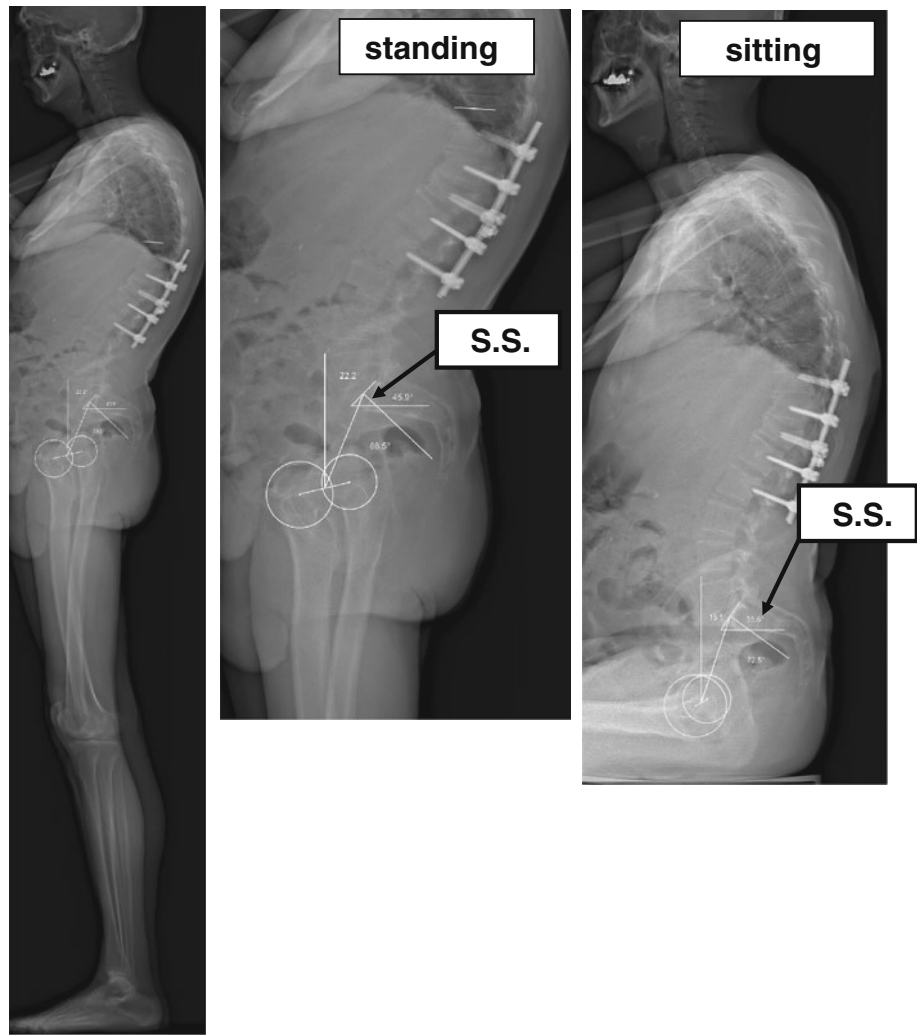
Fig. 6 Diagram of the seated position: posterior pelvic tilt with verticalization of the sacrum and decrease of the sacral slope. The incidence is invariable and does not change

the dorsal decubitus position to collect morphologic data for planning the hip prosthesis [14]. The information obtained must extrapolated prudently because it is not necessarily vertical in standing positions, and its tilt is highly variable in sitting positions [22]. Accordingly, for mean values of 3° in standing positions, the values reported while sitting were 17.5° [15] (Fig. 7).

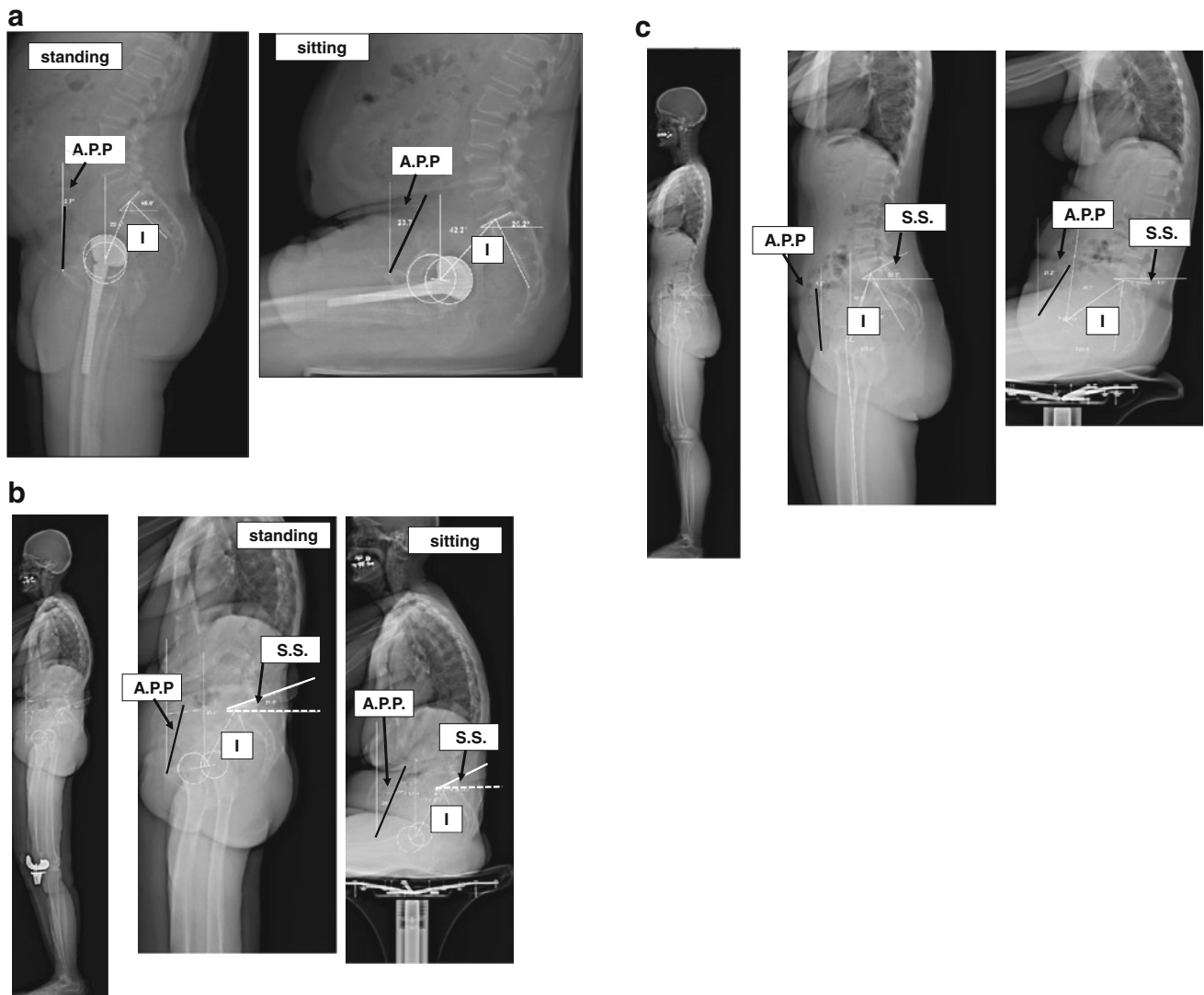## Influence of sagittal posture on the frontal and sagittal acetabular orientation in functional situations

Anatomic foundations

The interdependence between the sagittal tilt of the cup and the sacral slope is obvious when reading lateral images, seated or standing, of the lumbosacral joint [23].

In a standing position, the value of the sacral slope is high and the angle of the acetabular tilt is small. Inversely,

a

standing | sitting

A.P.P | A.P.P | I | I

b

standing | sitting

A.P.P | S.S. | I | A.P.P. | S.S. | I

c

A.P.P | S.S. | I | A.P.P | S.S. | I

Fig. 7 Variations in sagittal balance from the standing to the seated position. **a** Usual variation: The anterior pelvic plane tilts backwards in a seated position at the same time that the sacral slope is reduced from 45° standing to 26° seated; in this case, the available pelvic flexion is 19°. **b** Little postural variation of a stiffened lumbosacral joint (no available pelvic flexion). **c** Strong postural variations, sacral slope negative in a seated position (available pelvic flexion 38°)

in a seated position, the sacral slope diminishes and the acetabular tilt increases. From both AP and lateral positions, the THA cup appears more vertical in seated than in standing positions. Observational series of THA from diverse institutions [15, 17] report mean values of 49 to 52° for the frontal cup inclination in standing position and 57 to 64° while seated. At the same time the sagittal inclination is 36 to 47° standing and 51 to 58° seated. These variations in acetabular tilt contribute to modifying the "anterior opening" of the acetabulum and therefore the orientation of the functional "mobility cone" generated by the coxo-femoral joint (Fig. 8) [17, 24].
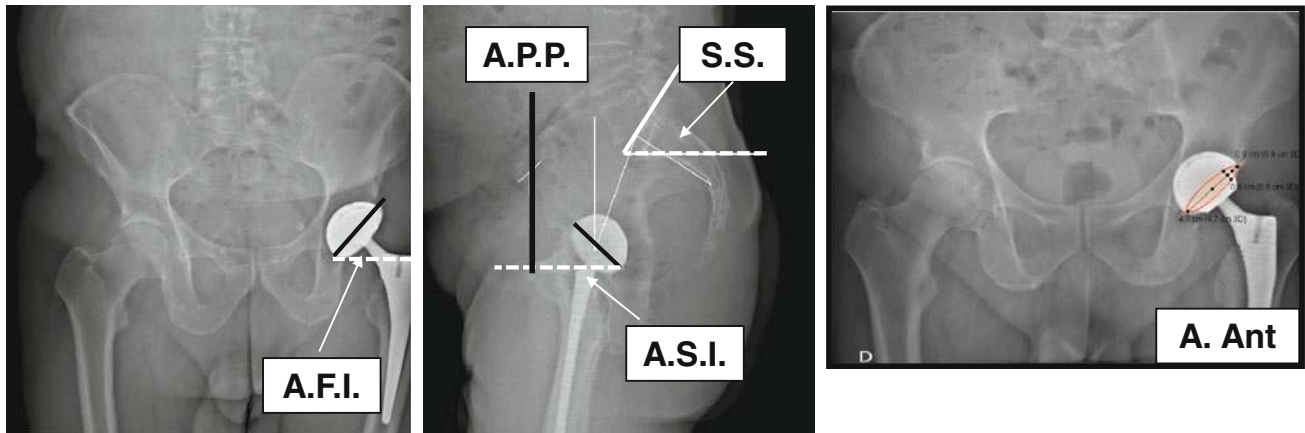
Modifications in the acetabular orientation produce consequences for the stability of hip arthroplasties and for all aspects of their tribology in the intermediate and long term [25–29].

Disruptions can come from atypical postures

Excess posterior tilt of the pelvis is often associated with postural imbalance to compensate for a forward tilt of the entire trunk. This postural adaptation verticalizes the cup from both the AP and lateral views and places the hips in a hyperextended position when standing. This solicitation of the available hip extension can lead to a posterior impingement. A typical example is posterior impingement of the hip prosthesis in standing position even though the cup was placed perfectly in accordance with the pelvic

standing

sitting
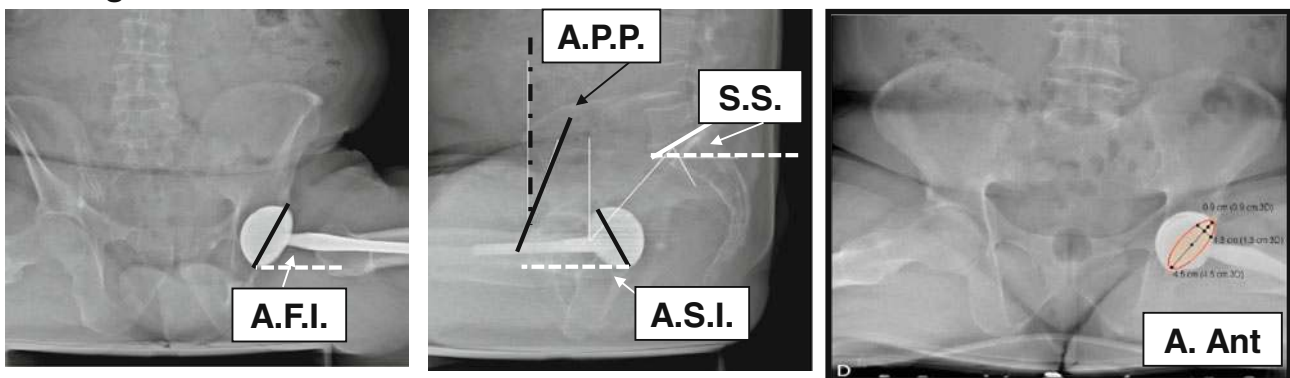
Fig. 8 Modification of the acetabular orientation from standing to seated position: increase in the acetabular frontal inclination (AFI.), the acetabular sagittal inclination (ASI), and the acetabular anterior opening (A Ant) measured by radiologic anteversion (Pradhan)

bone landmarks (Fig. 9). This situation can be encountered in native hips in the case of excessive posterior tilt of the pelvis (abnormal posture, trunk aging and induced posterior coxarthrosis) [30–33]. Analysis of these situations can be difficult because they involve simultaneously diseases of the spine and hips. Assessment of the available hip extension is thus essential to distinguish true and false inability to extend the hip fully (Figs. 10, 11). This analysis can be performed easily with EOS® technology, which makes it possible to individualize the available extension associated with the lumbosacral joint, that is, the extrinsic available extension, as well as the intrinsic available extension of each coxofemoral joint.

Inversely, excess anterior tilt of the pelvis in a seated position can cause anterior impingement (Fig. 12). In some cases, the anterior tilt of the acetabulum is also excessive in a standing position: the acetabulum is "horizontalized" from both AP and lateral views, as if the hips are permanently flexed when the subject is standing. This type of mechanism is suggested on native hips in anterior

impingements, especially in some repetitive athletic or occupational movements.

We also observed a mechanism of specific adaptation in hips that could not be fully extended secondary to coxarthrosis. The loss of range of motion of the abnormal hip results in a forward tilt of the pelvis when the patient tries to straighten up. When possible, the spine adapts by increasing lumbar lordosis, thus causing low back pain. Frequently, only one hip is involved. The test for available extension allows us to assess the phenomenon selectively.

Disturbances can come from atypical morphotypes

The angle of incidence is a morphologic parameter determinant for the adaptation of sagittal spinopelvic balance. It is associated with 2 functional indicators, pelvic tilt and sacral slope, by the formula I = SS + PT.

In subjects with a high angle of pelvic incidence, theoretical lumbar lordosis is greater as the range of adaptation

Fig. 9 The unusual posterior tilt of the pelvis can be detected on the AP standing image by the overly visible foramina obturata. After THA, this could result in a posterior impingement in standing position (anterior dislocation or subluxation)

of the sacral slope may also be. The femoral heads are projected forward relative to the sacrum and the acetabular anterior opening is less marked. The coxofemoral joints of these subjects have a greater theoretical available extension and therefore a better ability to adapt.

Inversely, in subjects with a low pelvic incidence angle, there is less theoretical lumbar lordosis and the adaptability of the sacral slope may be more limited. The femoral heads are embedded under the sacrum and the anterior opening of the acetabulum is more marked. Theoretically, these subjects have less available extension and a weaker capacity to adapt to sagittal imbalance (Fig. 13).

Influence of sagittal posture on cross-sectional acetabular cup orientation: anatomic and functional anteversion

Standard data

"Anatomic" anteversion or "morphological" anteversion is the angle between the AP pelvic axis and the acetabular axis when this is projected on to the transverse reference plane perpendicular to the longitudinal axis and the mid sagittal plane of the pelvis [6].

CT scan measurements are supposed to assess anatomic anteversion directly from cross-sectional slices. But the orientation of these slices in relation to the sagittal plane is left to radiologists to assess without any specific criterion for standardization, although it has a critical effect on the values of the angles measured. Fortuitously, they can be strictly perpendicular to the longitudinal axis of the pelvic bone landmarks. Most of the time these slices, perpendicular to the plane of the examination table, do not correspond to the anatomic plane because the position of the supine subject has a more or less marked sagittal pelvic tilt [17]. The variation in the anteversion measured is approximately 0.5 for 1° of rotation of the plane of the slice in relation to the pelvis [18, 34, 35].

An accurate understanding of lumbosacral posture and its influence on cup tilt shows us that the measurement of anteversion must not be linked to an arbitrary orientation of the slices to the machine stand. This point is essential for assessing the real acetabular anteversion of THA in terms of instability, especially when the lumbosacral joint is stiffened or in an atypical position [36–38].

The concept of functional anteversion

Functional acetabular anteversion is measured by the angle of the anterior opening of the cup, which varies as a
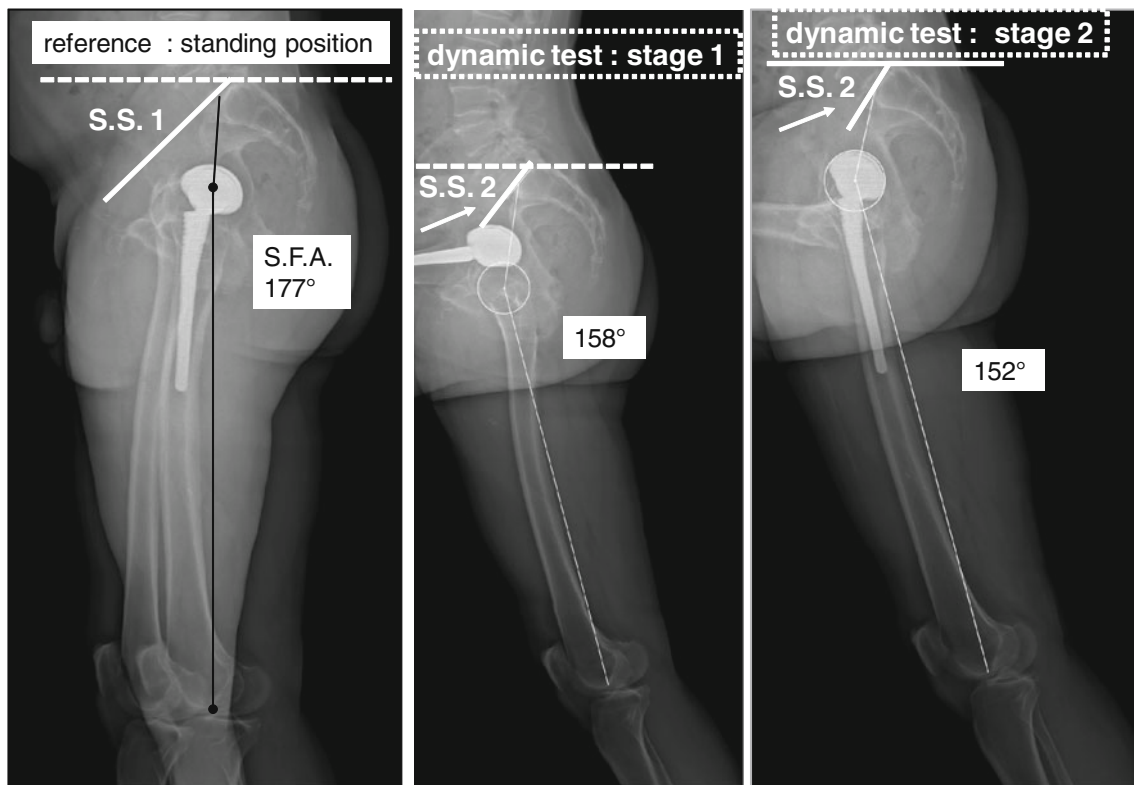
Fig. 10 Principle of measurement of the available spinopelvic extension (EOS® system). **a** The patient is assessed in a lateral standing position. (**b**, **c**) Each hip is then assessed in its maximum range of extension in standing position, placing the contralateral lower limb on a step such that it is in a position of maximum flexion of the coxofemoral joint. The extrinsic available extension is measured by the capacity to increase the sacral slope (SS 2–SS 1). The intrinsic available extension is measured by the variation of the sacro-femoral angle (SFA). The sacro-femoral angle is defined as the angle between the segment drawn from the middle of the sacral plate to the middle of the segment joining the centers of the femoral heads, and the segment joining the latter point (midpoint of the segment joining the center of the femoral heads) to the summit of the Blumensaat line, at the knee. The intrinsic extension is $177 - 152° = 25°$ for the THA side and $177 - 158° = 19°$ for the non-operated hip

function of pelvic tilt; it is calculated from the CT scan slices taken as a function of the sacral slope measured on the initial standard lateral image.

In a plane with the upper sacral plate, these slices reconstitute the sacral tilt angle, measured in a standing, sitting, or supine position. They make it possible to observe important changes in the cup orientation and improve our understanding of some coxofemoral joint dysfunctions.

In standing positions, there is less cross-sectional anteversion than in sitting positions, where the cup opens completely forward, thus favoring flexion of the hip and avoiding impingement at the femoral neck (Fig. 14). In supine positions, with the lower limbs extended, the pelvic tilt is often greater than in standing positions, lordosis more accentuated and anteversion still more reduced than when standing. In a series of 328 THA, we reported a mean anteversion of 31.7° standing, 38.8° seated, and 24.2° supine [17].

Globally, the "standard" CT scan measurements tend to overestimate anteversion in standing positions and to underestimate it in seated positions. Some subjects have completely stiff lumbosacral joints, and this significantly reduces the variations in acetabular anteversion between seated and standing positions. Such stiffening of the pelvis, in either a relative anterior or posterior tilt, may lead to a reproducible impingement situation. This phenomenon has been documented in the literature for deformities of the sagittal plane in spondylarthritis, in poorly adjusted lumbosacral arthrodesis (flat back), and especially in spinal aging [30–32, 39–41]. In these cases, we observed a reduction in lordosis and the appearance of an adaptive posterior pelvic tilt. The patient is standing, as if he were seated. This phenomenon reduces adaptation in the lumbosacral area and deviates the functional mobility cone of the coxofemoral joints towards flexion. The cup is permanently in hyper-anteversion, which is not bothersome during hip flexion but creates a problem of posterior impingement, especially in standing position: the person progressively loses his or her available extension (Fig. 15). The compensating hyperextension of the hips often has a limited impact in these patients, especially those who are elderly or have hip disorders. The last adaptation to attempt
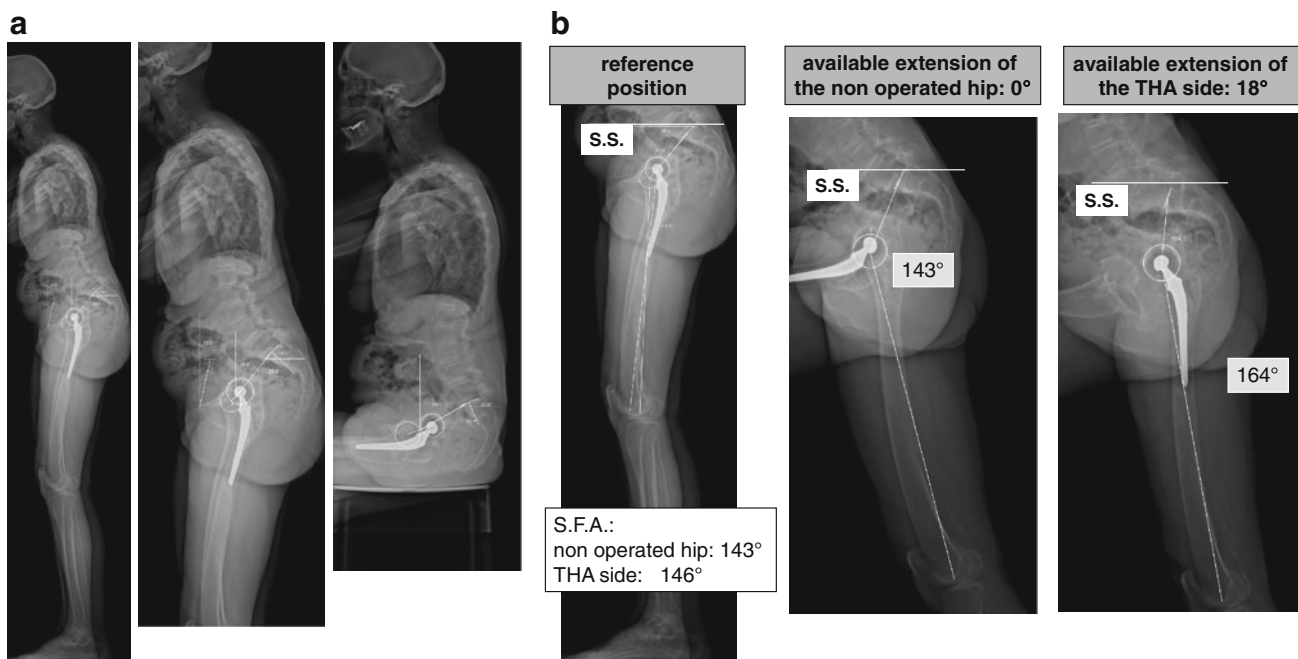
Fig. 11 a Situation of spinopelvic imbalance and hips that do not extend completely. The incidence is high; it is theoretically associated with elevated lordosis to keep the sagittal balance stable. In this case, the patient has an anterior imbalance not compensated by the hips (absence of hyperextension). This imbalance can be analyzed by searching for the available extension. **b** No role for the spine in recovering the extension: no available extrinsic extension because there is no modification of the sacral slope. There is no available extension for the non-operated hip (full extension truly impossible). Only the hip that underwent THA has an increase in available extension: from $164 - 146° = 18°$. The presence of this available extension on the operated side is evidence of an adaptive false inextendability in the reference standing position

Fig. 12 The abnormal anterior tilt of the pelvis in a seated position can lead to an anterior impingement of the hips with the risk of lesions of the labrum and the cartilage. In these cases, the available hip flexion required by the seated position is exaggerated, as the pelvic posterior tilt (pelvic retroversion) is not sufficient

Standard incidence   Low incidence   High incidence
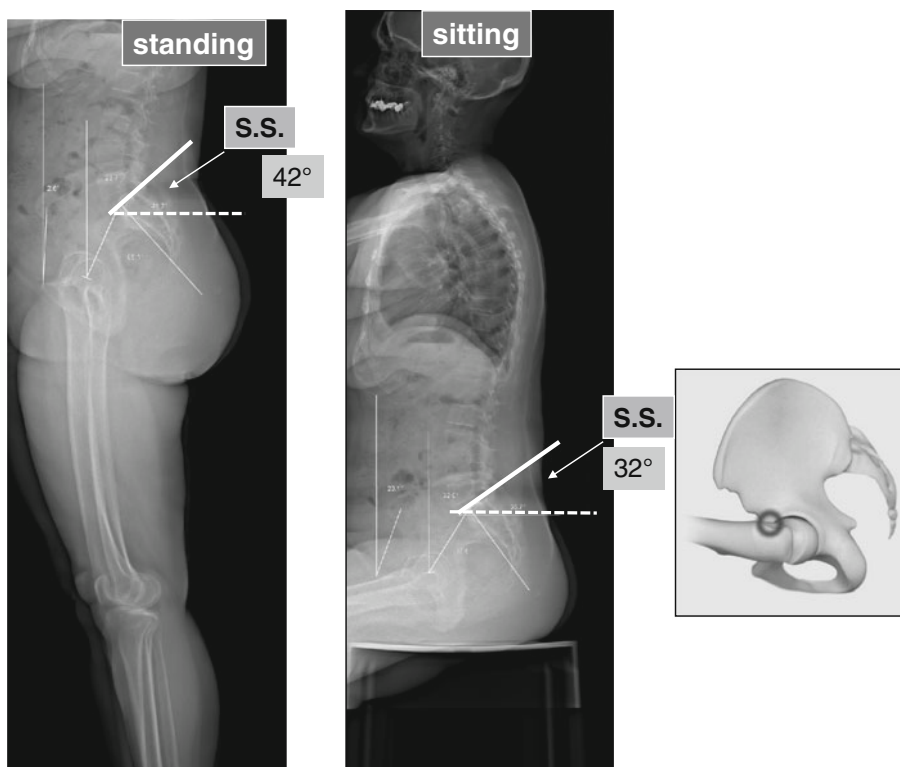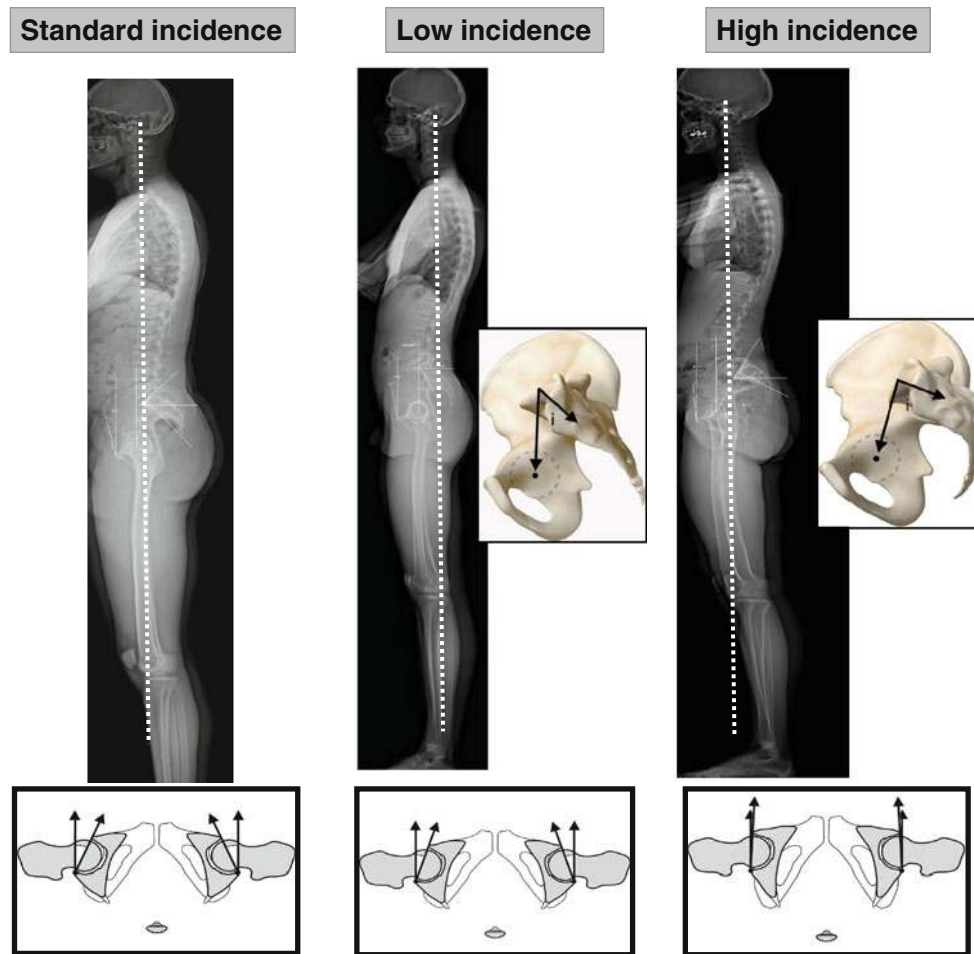
Fig. 13 Incidence is a morphologic characteristic determinant in the adaptation of the sagittal spinopelvic balance. In subjects with a high angle of pelvic incidence, lumbar lordosis is greater and the range of adaptation of the sacral slope may be greater. The anterior opening of the acetabulum is less marked, and the available extension of the hips greater. In the case of low pelvic incidence, lumbar lordosis is lower and the range of adaptation of the sacral slope more limited. The anterior opening of the acetabulum is more marked, but the theoretically available extension is lower at the hips

to improve balance is thus flexion of the knees, which enables additional posterior tilt of the pelvis.

Influence of axial rotation of the pelvis and the lumbopelvic region

Hip surgeons define a "normal" pelvic posture for imaging work-ups of subjects in a strictly anatomic position, with the two iliac wings projecting exactly and symmetrically, compared with the longitudinal axis of the trunk. Spine surgeons have been made aware of the three-dimensional view of the spine and the phenomenon of vertebral rotation that disturbs analysis of the lateral view. In this framework, the concept of the pelvic vertebra leads us to integrate pelvic rotation into the analysis of the overall trunk posture [42].

The use of standing and seated EOS® images in the subject's "usual" position is particularly instructive. Our database of complete EOS® acquisitions, both standing and seated, from over 2,500 patients, reveals the frequency of cases involving a forward hemipelvis and therefore a backward contralateral hemipelvis. This is expressed on the AP image by asymmetry of the projection of the iliac wings; the "forward" wing appears thinner than the other. Laterally, the two femoral heads and the two iliac wings are not superimposed. This "twisting" phenomenon is difficult to quantify with standard radiography because of the cone-shaped distribution of X-rays, which distorts interpretation of the image of the femoral head furthest from the scanner source. On the other hand, it is well analyzed by EOS® images in both the standing and seated positions, and 3D visualization of the pelvic position is possible. This

Fig. 14 In standing position, the sacral slope is high (40° approximately); the acetabulum appears more horizontal from both frontal and lateral views; the functional acetabular anteversion is weaker. In a seated position, the sacral slope is lower, sometimes negative, and the acetabulum appears more vertical from both the frontal and lateral views. The functional acetabular anteversion is more elevated
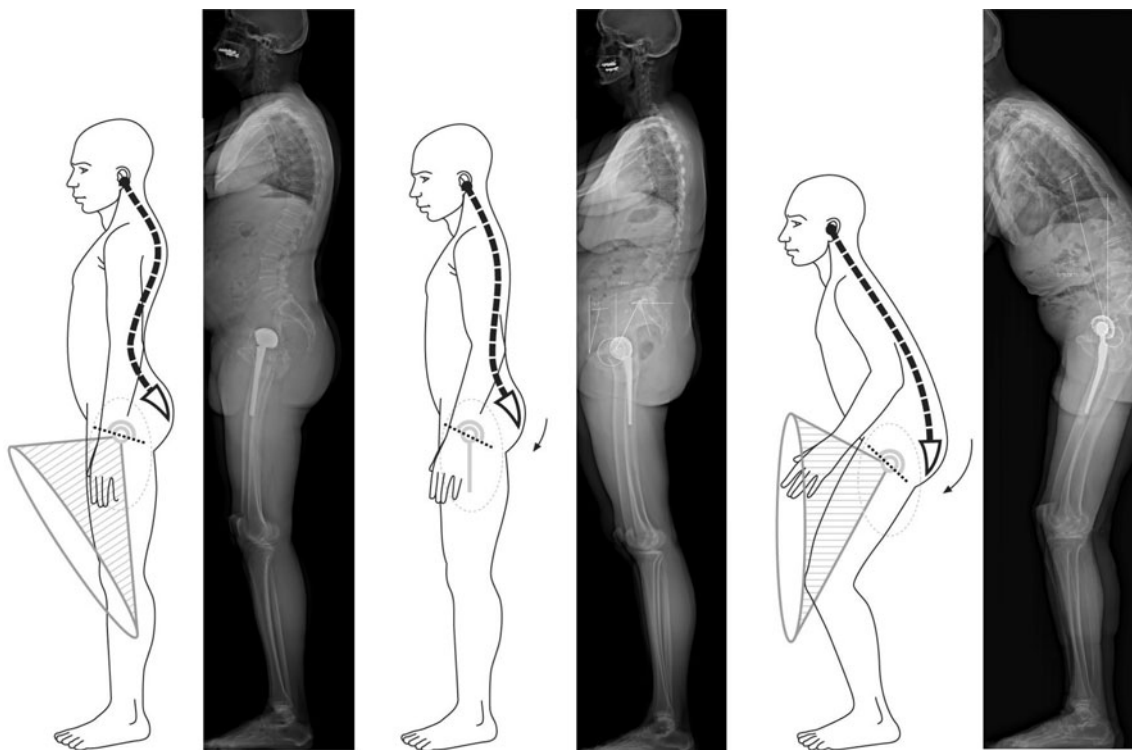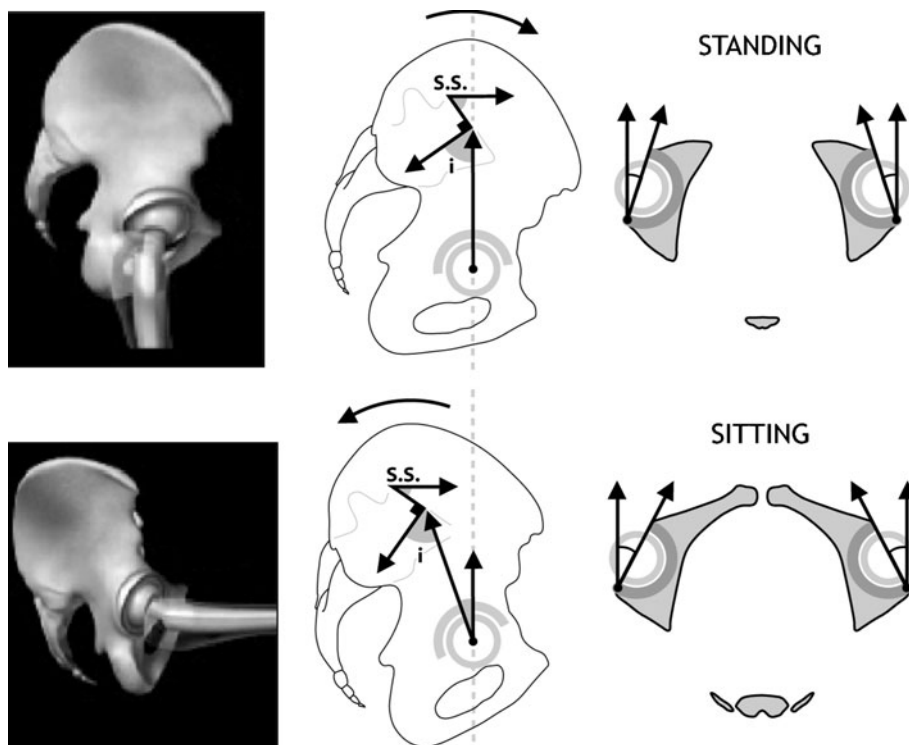
Fig. 15 Modifications of the functional mobility cone in cases of pelvic tilt disorders: in the case of a posterior tilt of the pelvis, the cone is deflected; even though the coxofemoral joints are perfectly mobile, the patient is using his available extension

situation of pelvic rotation is pushed to extremes in cases of scoliosis with the pelvic vertebrae included in the deformity (Fig. 16). The consequences on cup orientation can be significant, in particular for patients with THA, because of the induction of changes in functional anteversion, in both standing and seated positions.

Fig. 16 Substantial rotation of the pelvis associated with scoliosis: the THA is perfectly implanted relative to the bone landmarks but subluxated permanently forward in the standing position: pelvic rotation induced an abnormal acetabular anteversion in a standing position. Note that the pelvic rotation disappears in the seated position (patient is asymptomatic when sitting)

Conclusion

Comprehensive analysis of the pelvic and subpelvic sectors as part of the sagittal, frontal and cross-sectional balance of the trunk sheds new light on some spinal diseases and their relation to the pelvis.

Knowledge of the mechanics of the lumbosacral joint is essential both for the spine surgeon and for the surgeon implanting hip replacements in elderly subjects or those with abnormal sagittal, frontal or rotational posture and/or a large reduction in functional range of motion.

Analysis of sagittal trunk balance must not therefore stop at the simple analysis of standing lateral spine images. The position of the hips is essential and the interpretation of hips that do not extend completely must integrate the measurement of available extension. Seated images show us large variations in balance and lead us to take into account the concept of available flexion, which is essential in hip surgery and in situations of instability.

A comprehensive assessment of each patient and in particular of the complex comprising the spine, pelvis, and femur is essential for understanding each individual's adaptation to the imbalance induced by disorders of the spine or lower limbs. Monitoring the course of these patients and planning treatment strategies, surgical or not, can thus be rationalized and optimized.

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