Role of pelvic translation and lower-extremity compensation to maintain gravity line position in spinal deformity

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OBJECT Previous forceplate studies analyzing the impact of sagittal-plane spinal deformity on pelvic parameters have demonstrated the compensatory mechanisms of pelvis translation in addition to rotation. However, the mechanisms recruited for this pelvic rotation were not assessed. This study aims to analyze the relationship between spinopelvic and lower-extremity parameters and clarify the role of pelvic translation.

METHODS This is a retrospective study of patients with spinal deformity and full-body EOS images. Patients with only stenosis or low-back pain were excluded. Patients were grouped according to T-1 spinopelvic inclination (T1SPI): sagittal forward (forward, > 0.5°), neutral (−6.3° to 0.5°), or backward (< −6.3°). Pelvic translation was quantified by pelvic shift (sagittal offset between the posterosuperior corner of the sacrum and anterior cortex of the distal tibia), hip extension was measured using the sacrofemoral angle (SFA; the angle formed by the middle of the sacral endplate and the bicoxofemoral axis and the line between the bicoxofemoral axis and the femoral axis), and chin-brow vertical angle (CBVA). Univariate and multivariate analyses were used to compare the parameters and correlation with the Oswestry Disability Index (ODI).

RESULTS In total, 336 patients (71% female; mean age 57 years; mean body mass index 27 kg/m²) had mean T1SPI values of −8.8°, −3.5°, and 5.9° in the backward, neutral, and forward groups, respectively. There were significant differences in the lower-extremity and spinopelvic parameters between T1SPI groups. The backward group had a normal lumbar lordosis (LL), negative SVA and pelvic shift, and the largest hip extension. Forward patients had a small LL and an increased SVA, with a large pelvic shift creating compensatory knee flexion. Significant correlations existed between lower-limb parameter and pelvic shift, pelvic tilt, T-1 pelvic angle, T1SPI, and sagittal vertical axis (0.3 < r < 0.8; p < 0.001). ODI was significantly correlated with knee flexion and pelvic shift.

CONCLUSIONS This is the first study to describe full-body alignment in a large population of patients with spinal pathologies. Furthermore, patients categorized based on T1SPI were found to have significant differences in the pelvic shift and lower-limb compensatory mechanisms. Correlations between lower-limb angles, pelvic shift, and ODI were identified. These differences in compensatory mechanisms should be considered when evaluating and planning surgical intervention for adult patients with spinal deformity.

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KEY WORDS sagittal alignment; full-body radiography; T-1 spinopelvic inclination; compensatory mechanisms; pelvic shift; pelvic tilt; spine deformity

ABBREVIATIONS AA = ankle angle; ASD = adult spinal deformity; BMI = body mass index; CBVA = chin-brow vertical angle; C7PL = C-7 plumb line; GL = gravity line; KA = knee angle; LL = lumbar lordosis; ODI = Oswestry Disability Index; PI = pelvic incidence; PT = pelvic tilt; SFA = sacrofemoral angle; SS = sacral slope; SVA = sagittal vertical axis; TK = thoracic kyphosis; TPA = T-1 pelvic angle; T1SPI = T-1 spinopelvic inclination; T9SPI = T-9 spinopelvic inclination.


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ver the past few decades, there have been significant advances in the treatment of patients with adult spinal deformity (ASD) due to the development of spinal deformity analysis. Specifically, sagittal alignment has been analyzed in numerous studies that have demonstrated the importance of pelvic morphology in the setting of spinal pathology. In addition, correlations between spinal and pelvic parameters have been well documented in the asymptomatic population and in patients with spinal disease. Several authors have investigated the relationship between radiographic parameters and patient-reported outcomes. They demonstrated that sagittal alignment is significantly correlated with pain and disability in the setting of ASD.

In order to maintain a standing posture, the goal is to reach an upright position with minimal energy expenditure. In 1984, Vidal and Marnay were the first to describe relationships between global spinal alignment and pelvic position in weight-bearing subjects. Dubousset described the concept of the “conus of economy”: a narrow range within which the body can remain balanced without external support and minimize energy use when maintaining an optimal erect posture. To explain the concept of the conus of economy and economic standing balance, some authors have tried to analyze the relationship between the gravity line (GL) and spinal parameters in standing posture.

Prior studies have attempted to address the impact of sagittal plane deformity in the context of the whole body. The most commonly known parameter of global alignment is the C-7 plumb line (C7PL). While it is simple to measure, C7PL may not accurately reflect spinal alignment, as it is a radiographic parameter that does not provide information on foot position or a representation of the applied forces. Indeed, differences in C7PL and GL positions have been demonstrated when the C7PL increased, no changes in GL position in relation to the heels were observed (the mean distance between GL and the heels was 111 mm). Moreover, a poor correlation existed between C7PL and the true GL (r = 0.098; p < 0.3). In asymptomatic patients, GL is defined by a vertical line crossing the center of the mass of the entire body, which normally falls over the femoral heads and lies anterior to all vertebrae.

In 1995, Legaye et al. in a barycentremetric study was the first to analyze the relationship between the center of gravity and pelvic morphology. Since then, other studies have analyzed the relationship between radiographic spinopelvic parameters and the body GL with forceplate analysis of foot position. These studies demonstrated that GL has a rather fixed offset from T-9. The body attempts to maintain a center of mass within a narrow range of sway in relation to the feet in order to maintain an erect posture. However, spinal malalignment can lead to compensatory mechanisms that maintain a center of mass (i.e., GL) in close relation to the feet (in order to stay in the conus of economy). Pelvic translation and pelvic retroversion are 2 examples of these mechanisms. Other purported mechanisms include knee and ankle flexion. Thus, an increasing C7PL is associated with a posterior pelvic shift with respect to GL. Finally, age-related changes in spinal alignment were noted with an increase in the sacrum-C7PL distance in elderly patients.

As research continues to develop, it has become increasingly clear that radiographs of the cervical, thoracic, and lumbar spine are insufficient to fully describe the impact of spinal deformity on the whole body. In spinal deformity, in order to maintain a horizontal gaze in the erect posture, compensatory mechanisms are recruited not only in the spinal column but also in the pelvis and lower limbs. Therefore, understanding the various components of global alignment, from the head to the feet, is critical in the effective evaluation and treatment of ASD patients, and thus thorough workup of these patients requires full-body images.

Specifically, despite research in forceplate analysis, there is still a lack of information on the relationship between the lower extremities and pelvis in ASD. Changes in the hip, knee, and ankle joints, which compensate for sagittal malalignment, have been described but have not been accurately assessed from head to feet. Using full-body images (EOS imaging), this study aims to clarify the role of pelvic translation and analyze the relationships between spinopelvic parameters and lower-extremity parameters in adults with spinal pathology.

Methods

Patient Demographics

This study is a single-site retrospective analysis. Following institutional review board approval, records of patients who presented with spinal pathology and underwent full-body EOS radiography from head to feet between November 2012 and November 2013 were reviewed. The inclusion criteria allowed all adult patients (> 18 years of age) with degenerative spinal pathologies (scoliosis, kyphosis, spondylolisthesis), with or without previous spine surgery, who underwent full-body EOS images. Patients were excluded for the diagnosis of neuroscoliosis, a single diagnosis of low-back pain without any radiographic or MRI pathology, stenosis, fracture, or spinal tumor. Standard demographic information were recorded for each patient, including age, sex, and body mass index (BMI), as well as patient-reported outcomes as measured by the Oswestry Disability Index (ODI).

Biplanar Radiographic System

All patients underwent low-dose, head-to-feet, biplanar stereoradiographic imaging (EOS imaging). The protocol for image acquisition called for a weight-bearing, free-standing position with arms flexed at 45° in order to avoid superimposition with the spine. Ilharreborde et al. and Steffen et al. demonstrated that this position does not change the center of gravity position. The EOS system is a slot-scanning radiological device that consists of 2 x-ray sources, thereby allowing the simultaneous acquisition of 2 images. The 2 source-detector pairs are positioned orthogonally. Thus, the anteroposterior and lateral images are simultaneously acquired and generated while the whole system is vertically translated without vertical distortion.
Radiographic Parameters

All radiographic parameters were analyzed using Surgimap Software (Nemaris Inc.). The accuracy and reliability of this software have been assessed previously and are briefly summarized hereafter. The inter- and intraobserver reliability analysis revealed high agreement (intraclass correlation coefficient > 0.8) for all spinopelvic parameters, and the accuracy was below ± 0.5° for pelvic parameters and ± 5° for thoracic kyphosis (TK) and lumbar lordosis (LL).

Global alignment was assessed using the sagittal vertical axis (SVA), C7PL, T-1 spinopelvic inclination (T1SPi; the angle formed by the vertical reference line and the line between the center of the T-1 vertebral body and the center of the bicoxofemoral axis), T-9 spinopelvic inclination (T9SPi; the angle formed by the vertical reference line and the line between the center of the T-9 vertebral body and the center of the bicoxofemoral axis), and T-1 pelvic angle (TPA; the angle formed by the line between the center of the T-1 vertebral body and the bicoxofemoral axis and the line between the bicoxofemoral axis and the middle of the S-1 endplate). Fig. 1 demonstrates how to measure T1SPi and its relation to SVA.

Regarding regional alignment, the craniocervical module was assessed by measuring the cervical alignment with C0–2, C2–7, and the chin-brow vertical angle (CBVA; the angle between the vertical reference line and the line tangent to the eyebrow and chin) in order to analyze the horizontality of the patient’s gaze (Fig. 2).

The spinal and pelvic parameters included T1–12 kyphosis, L1–S1 lordosis, and the 3 pelvic parameters: pelvic incidence (PI), sacral slope (SS), and pelvic tilt (PT). The lack of lordosis was assessed by PI-LL mismatch.

In terms of lower-limb evaluation, hip extension was measured using the sacrofemoral angle (SFA; the angle formed by the middle of the S-1 endplate and the bicoxofemoral axis and the line between the bicoxofemoral axis and the femoral axis). Mangione described the SFA, and its value in an asymptomatic population was 191° ± 7°. The knee angle (KA) and ankle angle (AA) were also measured. In a previous forceplate study, the body GL maintains a fixed location relative to the heels (113–120 mm anteriorly, which corresponds to anterior cortex of the distal tibia), even with C7PL variations. In an effort to reproduce the forceplate studies, the pelvic translation was assessed and quantified in terms of the sagittal offset between the posterosuperior corner of sacrum and the anterior cortex of distal tibia (Fig. 3).

Statistical Analysis

After reviewing the sagittal parameters, patients were classified in 3 groups of spinopelvic alignments based on the normal distribution of T1SPi: the sagittal forward group included patients with a T1SPi > 75th percentile; the sagittal backward group included patients with a T1SPi < 25th percentile; and the neutral group included patients with a T1SPi between the 25th and 75th percentile (Fig. 4). T1SPi was chosen as the parameter to subdivide our patient population because it is a global measure of spinal alignment that has been previously used in the forceplate literature. Patients with T1SPi < 25% percentile and > 75% percentile were found to have corresponding SVA values that are established as being sagittal backward or sagittal forward, respectively, meaning that the C7PL falls behind or front of SI.

Data were statistically analyzed using Stata software (StataCorp). The normal distribution of the variables was verified using the Shapiro-Wilk test. The descriptive analysis (mean, range, and standard deviations) is reported for the radiographic parameters, demographic data, and health-related quality of life scores. Comparisons of the 3 groups were carried out using the ANOVA with Bonferroni post hoc test, and the relationship between the spinopelvic parameters, lower limbs, and ODI were assessed using Pearson correlation. The level of significance was set at p < 0.05.

Results

Patient Demographics

In total, 336 patients were included (71% female). The
mean age was 57.7 (± 15) years, the mean BMI was 27 kg/m², and 171 of the 336 patients (50.9%) had fusion to the sacrum and/or pelvis. Comparison of the demographic parameters among the 3 groups of sagittal alignment revealed no significant differences between the backward and neutral groups, but patients in the forward group were significantly older (Table 1).

**Univariate Analysis**

With the exception of TPA, all parameters were normally distributed. Stratification by group according to the distribution of the T1SPi (Fig. 5) revealed that patients in the forward group (n = 84) had a T1SPi greater than 0.48° (5.9° ± 7.7°), patients in the neutral group (n = 168) had a T1SPi between 0.48° and −6.27° (−3.5° ± 1.7°), and patients in the backward group (n = 84) had a T1SPi that was less than −6.27° (−8.8° ± 2.3°) (Table 2).

The analysis of differences across these 3 groups (Table 2) revealed that, with the exception of the cranial and cervical parameters, all radiographic parameters were significantly different. In line with the group definition, all global spinopelvic parameters (T1SPi, T9SPi, TPA, and SVA) were significantly greater in the forward subgroup.

The forward subgroup of patients had sagittal malalignment (anterior SVA of 110.9 mm with the lack of lordosis; PI-LL of 20.6°), and these patients recruited the following compensatory mechanisms in order to maintain an upright posture: pelvic retroversion (as demonstrated by increased PT of 24.1°), hip extension (198.3°), knee flexion (13°), and pelvic shift (−240.1 mm). The patients in the backward subgroup had a posterior SVA (−13.5 mm) with a posterior T9SPi (−16.0°), and there was no PI-LL mismatch. These patients had a large hip extension angle (207.2°) associated with an anterior pelvic shift (66.8 mm) with limited knee flexion (4.2°). Finally, the neutral patients had a small SVA (23.1 mm) with a PI-LL mismatch of 3.1°; the PT was 19.4° with a hip extension of 200.5° without knee flexion.

The ANOVA results revealed that the forward patients had a significantly smaller LL and TK, greater PI-LL mismatch, and significantly greater anterior T1SPi, TPA, and SVA. They had significantly greater knee and ankle flexion that were associated with significantly more posterior pelvic shift, whereas the backward group had significantly more posterior T1SPi, T9SPi, and SVA and more anterior pelvic shift with an SFA that was significantly more greater than the 2 other groups. The 3 groups had a CBVA between 0.7° and 1.4°.

All 3 groups had high ODI (49.6 ± 22.3 in the forward...
group; 35.2 ± 17.1 in the neutral group; 33.5 ± 20.7 in the backward group); however, ODI was significantly worse in the forward group (p = 0.001).

Multivariate Analysis

Analysis of the Pearson correlations revealed significant correlations between pelvic shift and the SFA (r = −0.150; p = 0.006), knee flexion (r = −0.633; p = 0.001), and AA (r = −0.194; p = 0.001). There were significant correlations between T1SPI and all compensatory mechanisms (Table 3). The correlations between craniovertebral parameters and lower limbs were weak. ODI had a significant negative correlation with pelvic shift (r = −0.365; p = 0.001) and the difference in KA and AA (r = 0.290; p = 0.01). ODI was negatively correlated with CBVA (r = −0.329; p = 0.06). However, no correlation existed between ODI and SFA, KA, or AA (Fig. 6).

Linear regression analysis showed a significant mathematical relationship between pelvic shift and all compensatory mechanisms (p < 0.05). The analysis of the coefficients revealed that a posterior pelvic translation was associated with pelvic retroversion (i.e., hip extension), flexion of the knee, and extension of the ankle as follows: pelvic shift = 9.17 × PT + 38.83 × KA − 69.76 × AA + 28.76.

Discussion

Increasing interest in sagittal plane analysis has led to a better understanding of the interaction between the spine and pelvis. However, only a few studies have documented the relationship between spinopelvic parameters and the lower extremities. In the case of anterior malalignment, in order to maintain GL position within a narrow range, different compensatory mechanisms occur: thoracic flattening, pelvic retroversion, and lower-limb responses such as hip extension, knee flexion, ankle flexion. With the recent development of the EOS system, full-body analysis can be performed in a standing position with low-dose irradiation, which has allowed the more thorough analysis of these compensatory mechanisms. Spine surgeons can now use EOS imaging to better understand how each patient utilizes various compensatory mechanisms, which need to be factored into the degree of deformity correction in order to achieve optimal postoperative alignment.

Group Description

In terms of global sagittal alignment, the 3 defined groups revealed specific adaptations in the lower limbs and pelvis in order to maintain an erect posture. Marked differences between groups were identified at several levels: the regional and global spine; pelvis; lower-limb alignment; and pelvic shift (Fig. 4).

In the backward group, SVA was posterior and the TPA was smaller than in a population with moderate disability (11.80° vs 14.10°). The spinal segment of the backward group was well aligned since TK and LL adapt to PL. However, moderate pelvic retroversion (24°) could lead to a negative T1SPI and was associated with a major hip extension and neutral knee and ankle positions. In this case of spinal alignment, pelvic retroversion and hip extension without knee flexion were combined with anterior pelvic shift.

In the forward group, SVA and TPA were high. In previous studies, high SVA and TPA were demonstrated to correspond to a high grade of disability. The lack of lordosis was important and all compensatory mechanisms were recruited. TK was flattened to reduce the anterior translation of the GL. However, in the case of TK with severe ankylosis, cervical hyperlordosis can be observed to maintain a horizontal gaze. The forward group was characterized by a retroverted pelvis, as defined as posterior rotation of the pelvis around the femoral heads thereby bringing the sacrum posterior to the coxofemoral joints, which is related to hip extension. Moreover, to compensate for this important anterior malalignment, there was major knee flexion associated with posterior pelvic shift as previously mentioned.

Patients in the neutral group had a T1SPI value that
was close to the T1SPi value in the asymptomatic population (−3.5° ± 1.7° and −1.4° ± 2.7°, respectively). However, the TPA and SVA were greater than in the asymptomatic population, perhaps because all patients in the present study group had spinal pathology. The spinal curves of the neutral group were adapted to the PI without pelvic retroversion. As expected, there was no compensation in the lower limbs with neutral hip, knee, and ankle position and a small anterior pelvic shift.

Relationship Between Spinopelvic and Compensatory Parameters
In this study, we divided patients with ASD into 3 categories based on T1SPi in order to distinguish between patients who are sagittally backward, neutral, and forward. This was done because these patients clinically present with different degrees of disability and recruit compensatory mechanisms differently and should be understood by clinicians as having different pathoanatomical processes that drive disability. Consistent with a previous study, 2 parameters of global alignment—T1SPi and TPA—had good correlations with compensatory mechanisms. Our findings further emphasize the importance of knee flexion as a lower-limb compensatory mechanism. These results are similar to those reported by Obeid et al. and Itoi, who show a weak correlation between knee flexion and LL (r = 0.375; p = 0.05), moderate correlation between knee flexion and PT (r = 0.411; p = 0.05), and good correlation between knee flexion and PI (r = 0.615; p = 0.05).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Backward Group (n = 84)</th>
<th>Neutral Group (n = 168)</th>
<th>Forward Group (n = 84)†</th>
<th>All Patients (n = 336)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age in yrs</td>
<td>56.1 ± 14.3</td>
<td>55.8 ± 16.2</td>
<td>63.3 ± 13.1</td>
<td>57.7 ± 15.3</td>
<td>0.005‡</td>
</tr>
<tr>
<td>Mean BMI in kg/m²</td>
<td>24.6 ± 4.6</td>
<td>26.9 ± 6.2</td>
<td>29.8 ± 7.9</td>
<td>27 ± 6.5</td>
<td>0.005‡</td>
</tr>
</tbody>
</table>

CM = cervical myelopathy (due to degenerative change and arthrosis); DSPL = degenerative spondylolisthesis; LSPL = lysis spondylolisthesis; NS = not significant.
* Values are presented as the number of patients (%) unless specified otherwise. Mean values are presented as ± SD.
† The forward group was older and had higher BMI than the other groups. No significant differences in sex or distribution of diagnoses were found.
‡ Significant differences within this group.

FIG. 5. T1SPi distribution. Figure is available in color online only.
between knee flexion and PI-LL mismatch \( (r = 0.523; \ p = 0.05) \). This suggests that as sagittal malalignment increases, knee flexion is potentially more important. Traditionally, ASD patients have been suboptimally corrected, and recognition of the differences in the recruitment of compensatory mechanisms is important for clinicians who aim to plan corrective surgeries to fully address a patient’s pathology and improve postoperative outcomes.

Since the barycentremetric study by Duval-Beaupere et al., researchers have attempted to further study the impact of sagittal plane alignment on biomechanical loads and degenerative changes of the spine. Several methods have been developed to identify the location of the center of gravity in the context of spine-related research. In 1992, Duval-Beaupere et al. described a method based on a gamma-ray scanner prototype that was combined with lateral radiography. Clinical use of this apparatus was limited by excessive radiation, cost, and length of time required to obtain the data, which prompted the development of alternative methods including forceplate technology. By combining GL and lateral full-spine analysis, comparisons were made between alignment parameters (e.g., SVA), pelvic parameters, and GL location. In 2008, Legaye and Duval-Beaupere proposed a computed estimation of the position of the GL in relation to L3 by using a predictive equation of the location of gravitational forces relative to the lumbar spine. The main findings of these gravitational studies were consistent with each other and used in the current study. In physiological and economic posture, the GL falls posterior to the femoral heads; under such conditions, no muscular electric activity is observed in the posterior spinal muscles. In the setting of sagittal plane deformity with an anterior truncal inclination, compensatory mechanisms are required to maintain the GL projection within the polygon of sustentation. As described by Lafage et al., anterior sagittal alignment is associated with a posterior shift of the pelvis in an effort to maintain a constant GL and offset the heels. To date, the mechanisms involved in this pelvic translation have not been described.

The pelvic shift parameter introduced in the current study aims to quantify the pelvic translation reported in forceplate literature. Pelvic shift correlated with ODI and lower-limb compensatory mechanisms, especially knee flexion. As shown in the linear regression, pelvic shift can

### TABLE 2. ANOVA results of radiographic data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Backward Group (n = 84)</th>
<th>Neutral Group (n = 168)</th>
<th>Forward Group (n = 84)*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>T1SPi, °</td>
<td>−8.8</td>
<td>2.3</td>
<td>−3.5</td>
</tr>
<tr>
<td>T9SPi, °</td>
<td>−16.0</td>
<td>4.2</td>
<td>−11.2</td>
</tr>
<tr>
<td>SVA, mm</td>
<td>−13.5</td>
<td>25.9</td>
<td>23.1</td>
</tr>
<tr>
<td>TPA, °</td>
<td>11.80†</td>
<td>11.95</td>
<td>15.01†</td>
</tr>
<tr>
<td>CBVA, °</td>
<td>0.7</td>
<td>8.5</td>
<td>1.4</td>
</tr>
<tr>
<td>C2–7–, °</td>
<td>−6.8</td>
<td>17.4</td>
<td>−7.9</td>
</tr>
<tr>
<td>T1–12, °</td>
<td>48.9†</td>
<td>20.4</td>
<td>47.3†</td>
</tr>
<tr>
<td>L1–S1, °</td>
<td>−54.1†</td>
<td>14</td>
<td>−50.8†</td>
</tr>
<tr>
<td>PI–LL, °</td>
<td>−1.3†</td>
<td>16.7</td>
<td>3.1†</td>
</tr>
<tr>
<td>PI, °</td>
<td>58.0†</td>
<td>14</td>
<td>54</td>
</tr>
<tr>
<td>PT, °</td>
<td>24.6†</td>
<td>11.7</td>
<td>19.4</td>
</tr>
<tr>
<td>SFA, °</td>
<td>207.2</td>
<td>10.7</td>
<td>200.5†</td>
</tr>
<tr>
<td>KA, °</td>
<td>4.2†</td>
<td>7.8</td>
<td>4.3†</td>
</tr>
<tr>
<td>AA, °</td>
<td>6.8</td>
<td>4.2</td>
<td>5.8</td>
</tr>
<tr>
<td>Pelvic shift, mm</td>
<td>66.8†</td>
<td>156</td>
<td>34.5†</td>
</tr>
</tbody>
</table>

* The forward group had higher T1SPi, T9SPi, SVA, TPA, PI, PT, knee flexion, ankle flexion, and pelvic shift along with hypokyphosis, loss of LL, and PI-LL mismatch.
† Denotes no significant differences between these groups.

### TABLE 3. Comparison of the correlations between spinopelvic and compensatory parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>T1SPi*</th>
<th>T9SPi</th>
<th>SVA</th>
<th>TPA</th>
<th>CBVA</th>
<th>C2–7</th>
<th>T1–12</th>
<th>L1–S1</th>
<th>PI–LL</th>
<th>PI</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFA</td>
<td>−0.305</td>
<td>−0.398</td>
<td>NS</td>
<td>0.617</td>
<td>−0.178</td>
<td>NS</td>
<td>NS</td>
<td>0.136</td>
<td>0.541</td>
<td>0.539</td>
<td>0.877</td>
</tr>
<tr>
<td>KA</td>
<td>0.477</td>
<td>0.228</td>
<td>0.596</td>
<td>0.584</td>
<td>0.121</td>
<td>NS</td>
<td>NS</td>
<td>0.375</td>
<td>0.523</td>
<td>0.241</td>
<td>0.411</td>
</tr>
<tr>
<td>AA</td>
<td>0.107</td>
<td>NS</td>
<td>0.275</td>
<td>0.437</td>
<td>−0.113</td>
<td>NS</td>
<td>0.254</td>
<td>0.373</td>
<td>0.186</td>
<td>0.442</td>
<td></td>
</tr>
<tr>
<td>Pelvic shift</td>
<td>0.618</td>
<td>0.39</td>
<td>0.768</td>
<td>0.766</td>
<td>−0.155</td>
<td>−0.141</td>
<td>−0.165</td>
<td>0.429</td>
<td>0.712</td>
<td>0.421</td>
<td>0.544</td>
</tr>
<tr>
<td>ODI</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>−0.329</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* T1SPi was correlated with all compensatory mechanisms.
be explained by pelvic retroversion associated with knee and ankle flexion. In addition to the lower-limb mechanisms, pelvic shift is correlated with global radiographic parameters, making it a valuable radiographic parameter and a high-yield method for assessing the link between the spine and the pelvis (Fig. 6). Previously, the relationship between the posterior displacement of the pelvis and pelvic retroversion in order to maintain the GL position was highlighted. These results are in accordance with previous studies, which showed a good correlation between the position of the GL and PT ($r = 0.746; p < 0.001$) and thus emphasized the role of pelvis rotation around the hip in maintaining the GL's position close to the feet.

In cases of anterior malalignment, mechanical loads are increased both by the anterior increase of the lever arm of gravity and by the excess of loads bound to the posterior muscular compensatory efforts. Dubousset described the “conus of economy” in order to explain the concept of an optimal erect posture with a minimum muscle action and energy expenditure. These concepts of economy and energy expenditure are in accordance with the close relationship between the anterior C7PL and posterior pelvic...
shift, which work together to maintain an optimal erect posture and horizontal gaze. Specifically, along the lines of muscular energy expenditure, Hopf et al.33 and Mahaudens et al.32 demonstrated that spinal sagittal malalignment created more muscular work. Indeed, forward spinal tilt associated with hip extension, knee, and ankle flexion involves increasing momentum around the hip, knee, and ankle joints, respectively. Considering muscular activity, anterior global malalignment of the spine is associated with an increased activity of the spinal extensor muscles in order to counteract the forward fall of the trunk. Considering the hip level, the hip extensors oppose flexion momentum. Knee flexion is controlled by the hamstrings and the gastrocnemius.49 In cases of sagittal malalignment, all of these muscles are recruited and responsible for energy expenditure in order to maintain GL position and erect posture. To best anticipate global alignment after spinal fusion, the preoperative evaluation of hip extension and mobility is mandatory. Failure to incorporate knee flexion can result in the inappropriate estimation of anterior malalignment and is thus a critical parameter to measure.

The significant correlation between ODI and pelvic shift emphasizes the role of compensatory mechanisms in driving disability in patients with sagittal malalignment. However, there was no correlation between KA and AA with CBVA or TK. Only a weak negative correlation existed between lower-limb parameters and the C2–7 angle. This could be explained by their opposite positions on the chain of compensation and potentially due to the later involvement of the craniovertebral portion depending on the previous thoracic segment compensation. Moreover, previous studies have demonstrated a huge variation in cervical alignment in asymptomatic populations (e.g., kyphotic or lordotic patients), which potentially canceled the statistical relationship between cervical and lower-limb compensation.

Study Limitations
This study has several limitations. First, the groups of patients were defined only by one criterion (T1SPi), and spinal disease was heterogeneous. Second, local compensatory mechanisms such as retrolithesis and hyperextension of the adjacent segments to a lumbar kyphosis were not assessed. Segmental measurements need to be done in order to assess the efficiency of these local mechanisms on sagittal alignment. Third, this is a radiographic study and the dynamic reserve of the lower limbs were not analyzed, such as the free hip extension as described by Hovorka et al.15 By design, this was a 2D analysis; therefore, pelvic twist and lower limbs torsion could not be analyzed. However, this would be possible with EOS-3D reconstruction. Finally, future studies should focus on applying this analysis to an asymptomatic population for comparison.

Conclusions
This study quantifies full-body alignment in a large population of patients with spinal pathologies and focuses specifically on analyzing the relationship between lower-limb angles with sagittal modifiers and ODI. Correlations between ODI, compensatory mechanisms, and pelvic shift were highlighted. These compensatory mechanisms are recruited in a sequential fashion in order to maintain GL position and an erect posture with horizontal gaze. Thus, the results of this study emphasize that pelvic translation and lower-limb mechanisms are compensatory parameters that are as important as the PT. These differences in compensatory mechanisms should be assessed in the global care of ASD patients and considered in preoperative planning.

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