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# Redefining physiological whole-body alignment according to pelvic incidence: normative values and prediction models

Marc Khalife<sup>1,2</sup> · Wafa Skalli<sup>3</sup> · Claudio Vergari<sup>3</sup> · Pierre Guigui<sup>1,2</sup> · Valérie Attali<sup>4,5</sup> · Rémi Valentin<sup>3</sup> · Olivier Gille<sup>6</sup> · Virginie Lafage<sup>7</sup> · Han Jo Kim<sup>8</sup> · Ayman Assi<sup>9</sup> · Emmanuelle Ferrero<sup>1,2</sup>

## Abstract

**Background context** Spinopelvic alignment assessment needs to account for pelvic incidence (PI).

**Purpose** This study aimed at providing normative values for commonly used parameters in whole-body alignment analysis based on PI.

**Design** Multicentric prospective study.

**Patient sample** This study included healthy volunteers with full-body biplanar radiograph in free-standing position.

**Outcome measures** All radiographic data were collected from 3D reconstructions: Sagittal vertical axis (SVA), T1 pelvic angle (TPA), spino-sacral angle (SSA), sagittal odontoid-hip axis angle (ODHA), pelvic parameters, sacro-femoral angle (SFA), knee flexion angle (KFA), ankle flexion angle (AA), Pelvic shift (PSh), lumbar lordosis (LL), thoracic kyphosis (TK) and cervical lordosis (CL).

**Methods** Population was divided into five groups according to PI. Normative values were described for each group. Linear regressions including age and PI provided prediction formulas for PT, TPA, SSA and SFA.

**Results** 642 subjects were included. Mean age was  $37.7 \pm 16.3$  years (range: 18–90). Mean PI in the cohort was  $49.3 \pm 9.5^\circ$ . LL, PT, SFA, SSA and TPA correlated with PI and age. ODHA, TK, CL and the other lower limb parameters were not associated with PI. All normative values across PI groups are provided for segmental, regional and global alignment parameters. Prediction formulas were:  $PT = -12.7 + 0.38 * PI + 0.14 * Age$ ,  $TPA = -16.9 + 0.34 * PI + 0.15 * Age$ ,  $SSA = 109.8 + 0.58 * PI - 0.19 * Age$ , and  $SFA = 173 + 0.39 * PI + 0.11 * Age$ .

**Conclusions** SSA, PT, TPA and SFA must be assessed according to patient's PI. This study provides normative values for each PI group, and predictive formulas taking age and PI into account. PI cannot be used to define thoracic and cervical curvatures.

**Level of evidence** II.

**Keywords** Pelvic incidence · Sagittal alignment · Lumbar lordosis · Normative values · Spinal shape

## Introduction

Sagittal alignment of the spine has been extensively studied in the literature, with reports associating sagittal malalignment with poor clinical outcomes [1, 2] and higher rates of mechanical complications after adult spinal deformity (ASD) surgery [3, 4]. Historical investigations focused on the association between pelvic parameters and lumbar lordosis [5], and a classification of lumbar lordosis based on sacral slope was proposed, which is now widely used [6,

7]. Although sacral slope presents the strongest correlation with lumbar lordosis among pelvic parameters [8], it is a positional parameter as opposed to pelvic incidence, which remains stable throughout life.

Over time, the analysis of spino-pelvic alignment has included thoracic kyphosis, cervical curvature, global parameters, and more recently, the lower limbs [9–11]. The first parameter used to describe global alignment of the spine was T9 sagittal offset [9, 12]. Several parameters have been proposed since then to describe sagittal alignment of

the spine. Most included the thoracic and lumbar regions but overlooked cervical curvature. Some of these parameters do not take pelvic retroversion into account, such as sagittal vertical axis (SVA) and T1 Spino-pelvic inclination (T1SPi) [13].

More recently, T1pelvic angle (TPA) and spino-sacral angle (SSA) have been described to assess thoracolumbar alignment [14, 15]. These parameters take into account patients' compensatory pelvic retroversion. Last, lower limb parameters are commonly used to assess global alignment as they play a major part in malalignment compensation [16]. Among them is the sacro-femoral angle (SFA), measured between the pelvic incidence axis and the line joining femoral head to condyles. The geometrical definitions of these three commonly used parameters imply a correlation with pelvic incidence. Sagittal alignment may need more thorough assessment to help prevent mechanical complications in ASD patients. Consequently, SFA, TPA and SSA values may have to be interpreted according to the patient's pelvic incidence, as it has already demonstrated for pelvic tilt and lumbar lordosis [17, 18].

Studies considering the whole-body postural alignment remain scarce. Hence, proposing a whole-body stratification based on pelvic incidence appears of interest to enhance alignment comprehension and patients' categorization. Such stratification is relevant in the setting of deformity, degenerative and traumatology spinal surgery. This study aimed to stratify physiological sagittal whole-body alignment based on pelvic incidence in a large cohort of healthy volunteers from young age to elderly subjects, with normative values for commonly used parameters in the whole-body alignment analysis.

## Methods

### Population

This multicentric study included healthy volunteers aged over 18 from previous studies, as well as newly enrolled subjects [19–22]. Volunteers presented no major pain in the spine, hip or knee. Exclusion criteria were any musculoskeletal deformity, scoliosis with a Cobb angle  $> 15^\circ$ , isthmic or degenerative spondylolisthesis, lumbosacral transitional anomalies, history of spinal surgery, and hip or knee replacement. Elderly subjects with mild degenerative changes were not excluded. All participants had a full-body biplanar radiograph (EOS™ system, Alphatec, CA, USA) in free-standing position (in upright position, fingers positioned on the cheeks or clavicles, and one foot slightly forward) [23]. A subset of volunteers had a health-related quality of life (HRQoL) questionnaire including lumbar

visual analog scale (L-VAS), Oswestry Disability Index (ODI) and SF-12. This study was approved by regional ethics committees (approval N° 6001 and 6061 C.P.P. Ile-de France VI and FM 312 ethical committee at the Saint-Joseph University, Beirut). All participants provided their informed written consent.

### Parameters

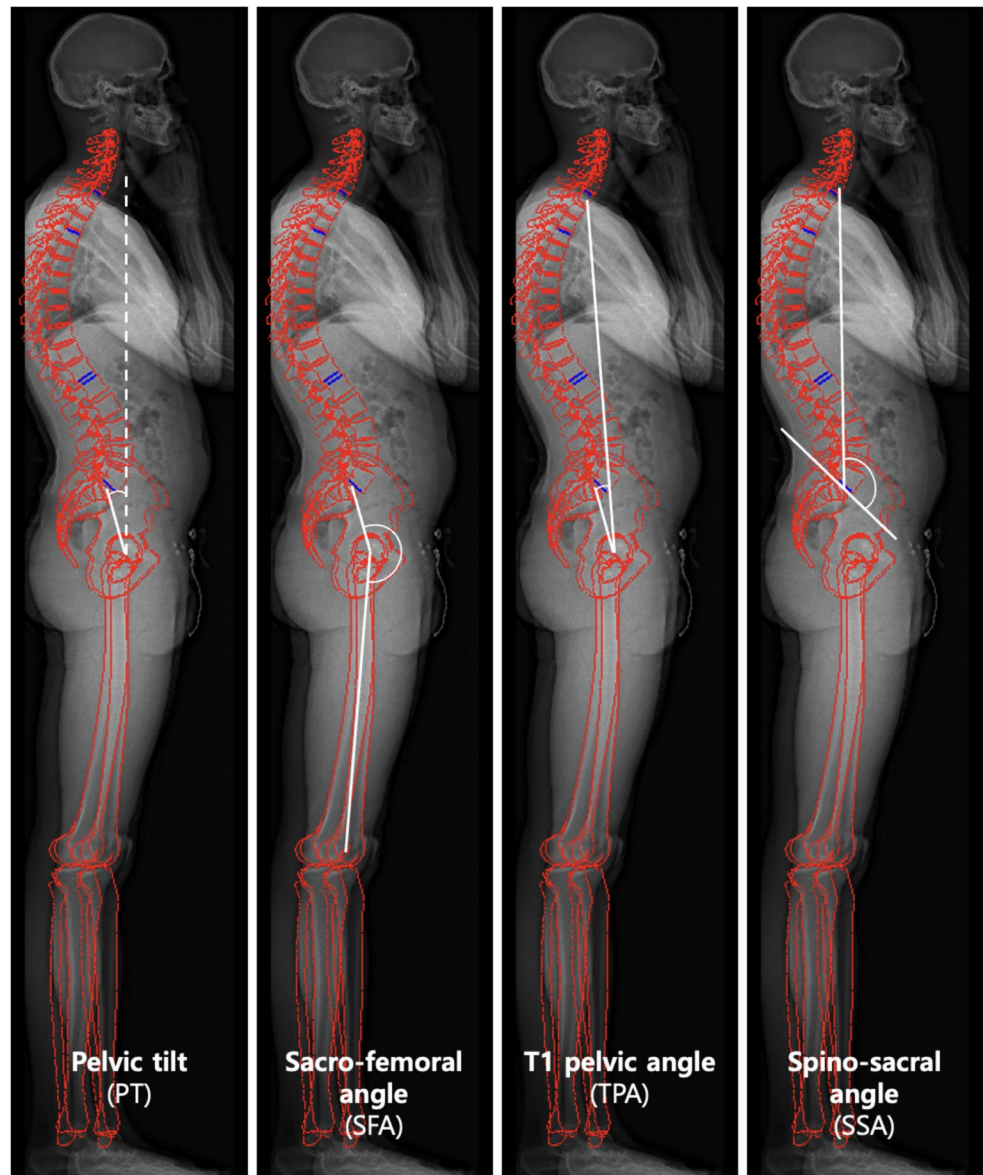
Spino-pelvic and lower limb three-dimension reconstructions were performed by a specifically trained physician, according to previously validated semi-automated methods [24, 25]. First, the spinal line from C3 to L5 was drawn by the user on the frontal and lateral views. The software then generated a 3D spine reconstruction and retro-projected the 3D models of the vertebrae on the radiographs. This model was then manually adjusted by the user to precisely fit vertebral contours visible on the radiographs. Similarly, the 3D models of the pelvis and lower limbs were carried out, first by defining anatomical reference points on bone contours and then by adjusting the generated reconstruction. Last, the odontoid tip was marked.

The following radiographic parameters were all obtained from the 3D reconstructions:

- *Global spinal alignment parameters:* Sagittal vertical axis (SVA), T1 pelvic angle (TPA), spino-sacral angle (SSA) (Fig. 1), T1 spino-pelvic inclination (T1SPi) and sagittal odontoid-hip axis angle (ODHA) [26].
- *Spinal parameters:* Maximum lumbar lordosis (LLmax) was measured from the upper endplate of inflexion point vertebra to the S1 plateau, distal LL (LLdist) from the upper endplate of lumbar apex to S1 plateau and proximal LL (LLprox) from the inflexion point vertebra upper endplate to lumbar apex upper endplate. LL was also assessed from L1 to S1, L4 to S1 and L1 to L4. Each lumbar vertebral body and disc angle was measured between the directly adjacent vertebral endplates. Regional angulations, used in traumatology, are measured between overlying vertebra upper endplate and lower endplate of the underlying vertebra (for L5: from L4 upper endplate to S1 plateau) [27]. The locations of lumbar apex and thoracolumbar inflexion point were noted.

TK was measured from T1 upper endplate to L1 upper endplate, further broken down into three equal regions: T1-T5, T5-T9 and T9-L1 [28]. Maximum thoracic kyphosis (TKmax) was measured from T1 upper endplate to inflexion point vertebra upper endplate. Cervical lordosis (CL) was measured between C3 lower endplate and T1 upper endplate.

**Fig. 1** Illustration of PT, SFA, TPA and SSA measurement



- *Pelvic parameters:* Standard pelvic parameters were collected: pelvic incidence (PI), pelvic tilt (PT) and sacral slope (SS) (Fig. 1) [5].
- *Lower limb parameters:* Sacro-femoral angle (SFA), Knee flexion angle (KFA), Ankle flexion angle (AA) and Pelvic shift (PSh) (Fig. 1) [29]. These parameters result from the left and right lower limbs values mean.

### Statistical analysis

All variables were tested for normality using Shapiro-Wilk's test. First, a global description of the cohort was made, with parameters expressed by their means  $\pm$  standard deviations (SD). By convention, lordosis is expressed by negative values as opposed to kyphosis which is given with positive ones. The relationships between PI and the other

studied parameters were investigated with focused principal component analysis and correlation table, using Spearman's coefficients. Correlations between radiographic parameters and age were also sought.

Empirically, the study population was then divided into five groups according to pelvic incidence, using Jenks' natural breaks optimization method. This method aims at reducing variance within classes and maximizing inter-class variance. Overall differences of radiographic parameters among PI subsets were assessed using ANOVAs for normally distributed variables or Kruskal-Wallis tests otherwise. The differences in lumbar apex and thoracolumbar inflexion vertebra locations were assessed using Pearson's  $\chi^2$  tests.

Further, multiple linear regressions were performed for the four variables of interest (PT, SSA, TPA and SFA)

including PI and age in the model to provide parameters prediction equations. Correlations between measured and calculated parameters were assessed and plotted.

All statistical analyses have been carried out using RStudio (version 1.2.1578), with p-values lower than 0.05 considered significant.

## Results

### Cohort description

Six hundred and forty-two subjects were included in the analysis, with 50.9% of females ( $n=327$ ). Mean age was  $37.7 \pm 16.3$  years, ranging from 18 to 90 years old. Mean pelvic incidence in the whole cohort was  $49.3 \pm 9.5^\circ$ . Table 1 summarizes radiographic parameters in the study population. Mean L-VAS was  $1.1 \pm 1.7$ , ODI was  $2.8 \pm 5.6$  (maximum ODI score was 34%) and SF12 were  $53.7 \pm 6.2$  and  $51.8 \pm 8.1$  respectively for physical and mental components.

Pelvic incidence presented significant correlations with several pelvic and lumbar parameters, SFA, TPA, and SSA, whereas there was no correlation with thoracic and cervical curvatures (Fig. 2). Pelvic tilt, TPA, SSA and SFA also

presented significant correlations with age, with correlation coefficients of 0.33, 0.33, -0.22 and 0.25 (all  $p$ -values  $< 0.001$ ), indicating more anterior global alignment in elderly, with greater pelvic retroversion (Table 2).

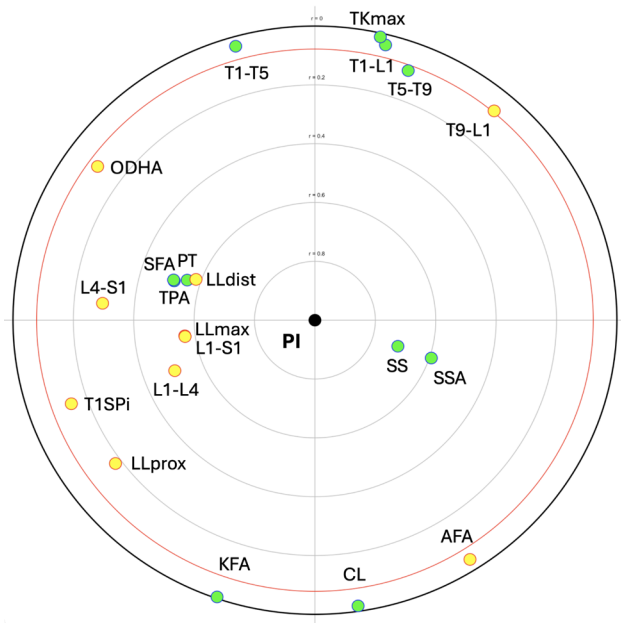
### PI groups

The cohort was divided into five PI classes: “Very low” ( $PI < 39^\circ$ ) including 83 subjects, “Low” ( $39^\circ; 47^\circ$ ) including 184 subjects, “Average” ( $47^\circ; 55^\circ$ ) including 211 subjects, “High” ( $55^\circ; 63^\circ$ ) including 123 subjects, and “Very high” ( $PI > 63^\circ$ ) including 41 subjects. All normative values across PI groups are provided in Table 3. TPA, SSA, SFA, SS and PT increased significantly for each PI group (Table 3). Thoracic kyphosis, cervical curvature and lower limb parameters apart from SFA did not significantly vary according to PI groups (Fig. 3). Although statistically significant, ODHA and T1SPi variation across PI groups was negligible (Table 3). There were no significant differences in HRQoL scores across PI groups (*not shown*).

**Table 1** Demographic and radiographic alignment parameters description in the whole cohort

$n=642$	Mean	Median	S.D.	Min	Max	Shapiro
Age (years)	37.7	32.0	16.3	18.0	90.0	$< 0.001^*$
BMI ( $kg.m^{-2}$ )	24.7	24.2	4.5	16.4	60.6	$< 0.001^*$
PI ( $^\circ$ )	49.3	49.2	9.5	24.9	87.3	$< 0.001^*$
PT ( $^\circ$ )	11.3	10.9	6.7	-7.0	32.9	0.34
SS ( $^\circ$ )	38.0	38.0	8.0	13.8	66.7	0.30
<i>Spinal curvatures</i>						
LLmax ( $^\circ$ )	-58.6	-58.7	11.1	-101.5	-19.5	0.10
LLprox ( $^\circ$ )	-23.6	-23.1	7.2	-48.7	-2.7	0.01*
LLdist ( $^\circ$ )	-35.0	-34.9	8.5	-67.9	-4.6	0.30
L1-S1 ( $^\circ$ )	-56.9	-57.2	11.3	-102.5	-14.4	0.01*
L1-L4 ( $^\circ$ )	-20.4	-21.0	8.4	-43.5	8.7	0.11
L4-S1 ( $^\circ$ )	-36.5	-36.5	7.2	-59.8	-4.6	$< 0.001^*$
TKmax ( $^\circ$ )	56.2	55.7	10.9	27.2	97.0	0.08
T1-L1 ( $^\circ$ )	50.9	50.6	10.9	21.6	91.3	0.02*
T1-T5 ( $^\circ$ )	19.6	19.3	8.1	-6.0	59.7	$< 0.001^*$
T5-T9 ( $^\circ$ )	23.5	23.2	7.1	-10.2	49.0	$< 0.001^*$
T9-L1 ( $^\circ$ )	7.9	7.8	7.7	-14.0	37.7	$< 0.001^*$
CL ( $^\circ$ )	-5.7	-5.6	11.0	-41.9	32.4	0.98
<i>Global alignment</i>						
ODHA ( $^\circ$ )	-2.4	-2.5	2.5	-9.3	8.7	$< 0.001^*$
TPA ( $^\circ$ )	5.6	5.3	6.6	-13.4	27.5	0.02*
SSA ( $^\circ$ )	131.3	131.3	8.9	96.7	161.8	0.02*
T1SPi ( $^\circ$ )	-5.7	-5.7	2.5	-13.5	6.5	0.02*
<i>Lower limbs parameters</i>						
PSH (mm)	16.6	17.3	26.1	-69.8	108.0	$< 0.001^*$
SFA ( $^\circ$ )	196.4	196.3	7.5	175.4	219.4	0.55
KFA ( $^\circ$ )	4.8	4.0	3.2	0.0	16.9	$< 0.001^*$
AFA ( $^\circ$ )	-2.1	-2.1	2.6	-13.0	5.8	0.06

**Fig. 2** Principal component analysis (PCA) focused on pelvic incidence, and correlation table with PI. In PCA, green dots tag variables positively related to PI whereas yellow dots mark negative relationships. Significant relationships are located inside the red circle. In the table, significant correlation coefficients are marked with a “\*”



	r	p
Age	0.08	0.05
BMI	0.15	<0.001*
PT	0.55	<0.001*
SS	0.68	<0.001*
LLmax	-0.55	<0.001*
LL prox	-0.21	<0.001*
LLdist	-0.54	<0.001*
L1-S1	-0.55	<0.001*
L1-L4	-0.51	<0.001*
L4-S1	-0.27	<0.001*
T1-L1	0.02	0.59
T1-T5	0.02	0.61
T5-T9	0.07	0.07
T9-L1	-0.07	0.06
TKmax	0	0.89
CL	0.03	0.49
ODHA	-0.11	0.008*
TPA	0.53	<0.001*
T1SPi	-0.13	0.001*
SSA	0.58	<0.001*
SFA	0.50	<0.001*
KFA	0.01	0.71
AFA	-0.05	0.17

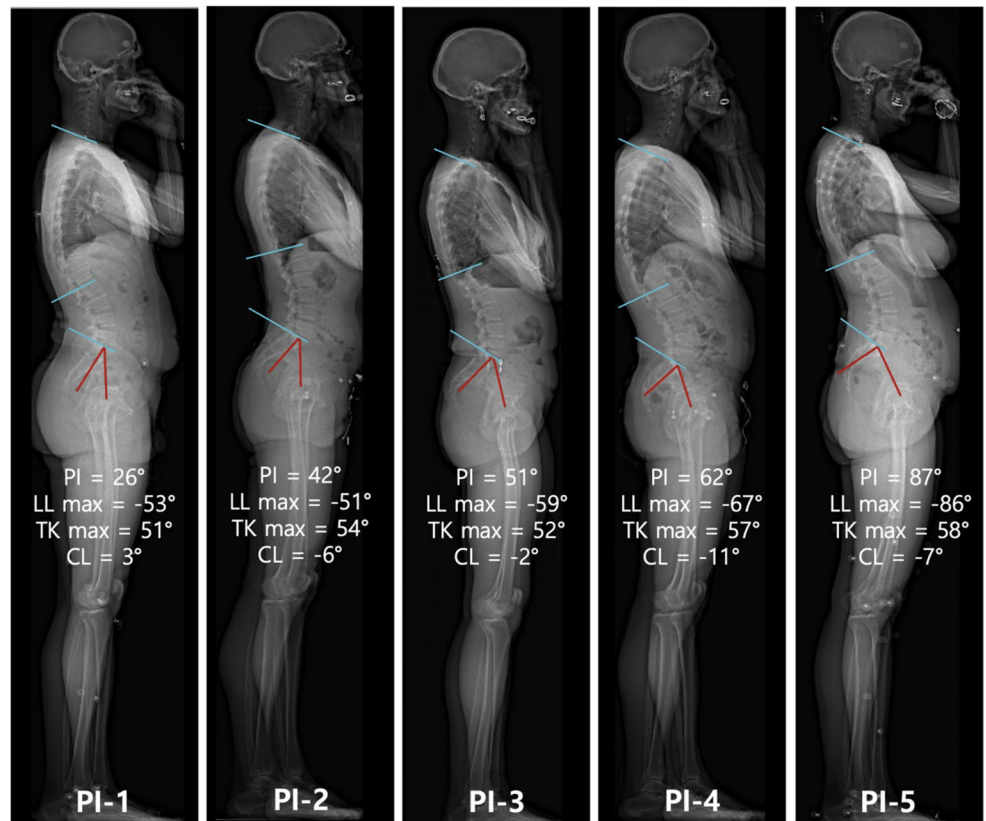
**Table 2** Correlation of radiographic parameters with pelvic incidence and age, with respective p-values. Significant p-values are marked with a “\*” if lower than 0.05

Parameters	Correlation with PI	p	Correlation with age	p
PT	0.55	< 0.001*	0.33	< 0.001*
SS	0.68	< 0.001*	-0.20	< 0.001*
<i>Spinal curvatures</i>				
LLmax	-0.55	< 0.001*	0.15	< 0.001*
LLprox	-0.21	< 0.001*	0.07	0.07
LLdist	-0.54	< 0.001*	0.14	< 0.001*
L1-S1	-0.55	< 0.001*	0.16	< 0.001*
L1-L4	-0.51	< 0.001*	0.09	0.03*
L4-S1	-0.27	< 0.001*	0.13	0.001*
TKmax	0	0.89	0.20	< 0.001*
T1-L1	0.02	0.59	0.16	< 0.001*
T1-T5	0.02	0.61	0.06	0.13
T5-T9	0.07	0.07	0.11	0.005*
T9-L1	-0.07	0.06	0.06	0.11
CL	0.03	0.49	-0.17	< 0.001*
<i>Global alignment</i>				
ODHA	-0.11	0.008*	0.05	0.17
TPA	0.53	< 0.001*	0.33	< 0.001*
SSA	0.58	< 0.001*	-0.22	< 0.001*
T1SPi	-0.13	0.001*	0	0.85
<i>Lower limbs</i>				
PSH	0.08	0.05	-0.12	0.003*
SFA	0.50	< 0.001*	0.25	< 0.001*
KFA	0.01	0.71	-0.08	0.05
AFA	-0.05	0.17	-0.19	< 0.001*

**Table 3** Radiographic parameters normative values according to PI groups, expressed by means±standard deviation. Significant differences among groups are marked with a “\*” if *p-values* < 0.05, and with “†” if *p-value* < 0.001. PI groups are respectively: “very low” (PI<39°), “low” (39°;47°), “average” (47°;55°), “high” (55°;63°), and “very high” (PI>63°)

PI groups	PI-1 (<39°)	PI-2 (39–47°)	PI-3 (47–55°)	PI-4 (55–63°)	PI-5 (>63°)
n	83	184	211	123	41
Age (years)	36.4±17.5	36.4±16.1	38.3±16.4	38.9±15.8	39.1±15.6
Age≥60 (%)	15.7%	15.2%	14.2%	13.8%	12.2%
† PI (°)	34.4±3.3	43.4±2.3	50.8±2.2	58.6±2.3	69.8±5.6
† PT (°)	6.0±5.8	8.4±5.7	12.0±5.8	15.3±5.3	18.9±5.7
† SS (°)	28.4±5.8	35.0±5.7	38.7±6.0	43.3±5.5	50.9±6.6
<i>Spinal curvatures</i>					
TKmax (°)	54.6±10.3	57.3±11.3	56.0±9.8	56.7±11.7	54.6±12.5
T1-L1 (°)	48.3±10.0	52.0±11.5	51.0±9.7	51.2±11.7	49.9±12.1
T1-T5 (°)	19.0±8.5	19.9±7.8	19.2±8.3	19.8±7.5	20.2±8.9
T5-T9 (°)	21.7±7.4	23.5±6.5	23.6±6.9	24.4±7.9	23.2±7.0
T9-L1 (°)	7.6±7.5	8.5±7.7	8.1±7.4	7.1±8.2	6.5±7.1
CL (°)	-5.0±9.7	-6.9±10.6	-5.5±11.6	-5.1±11.6	-5.1±11.3
<i>Global alignment</i>					
* ODHA (°)	-1.9±2.1	-2.1±2.7	-2.5±2.3	-2.7±2.8	-3.0±2.2
† TPA (°)	0.9±6.1	3.0±5.8	6.2±5.9	9.2±5.4	12.6±5.7
† SSA (°)	122.1±7.6	128.5±7.1	132.1±7.3	136.1±6.7	143.2±7.9
* TISPi (°)	-5.1±2.0	-5.4±2.5	-5.9±2.4	-6.2±2.9	-6.3±2.6
<i>Lower limb parameters</i>					
PSH (mm)	14.1±30.2	15.3±26.1	16.3±24.4	20.4±27.4	18.2±20.9
† SFA (°)	191.0±6.6	193.5±6.4	197.1±6.9	200.7±6.0	204.5±6.6
KFA (°)	4.5±3.5	4.7±3.1	5.0±3.3	4.3±2.7	5.4±3.2
AFA (°)	-1.8±2.6	-2.1±2.5	-2.2±2.9	-2.4±2.4	-1.8±2.6

**Fig. 3** One example of lateral view X-ray for each PI group. Maximum thoracic kyphosis (TKmax) and cervical lordosis (CL) do not vary according to PI



## Lumbar lordosis

All regional and global LL parameters increased across PI groups (Table 4). There was no significant variation in L5-S1 disc across groups, and L4-L5 disc lordosis increased by 2° between extreme PI groups. However, LL increase resulted from an increased lordosis in the discs from L3-L4 to T12-L1 and vertebral body lordosis at all levels (Table 4). Lumbar apex and inflexion points significantly differed between PI groups, moving cranially along with PI increase (both *p-values* < 0.001) (Fig. 4). While L4 was the most common lumbar apex in each PI subset, L5 location decreased in favor of L3 as PI increased. In the low PI group, the most common inflexion point vertebra was L2 whereas it was T12 in the very high PI group.

## Prediction formulas

According to multivariate linear regressions, prediction formulas for PT, TPA, SSA, SFA and LLmax relatively to age and PI are as follows:

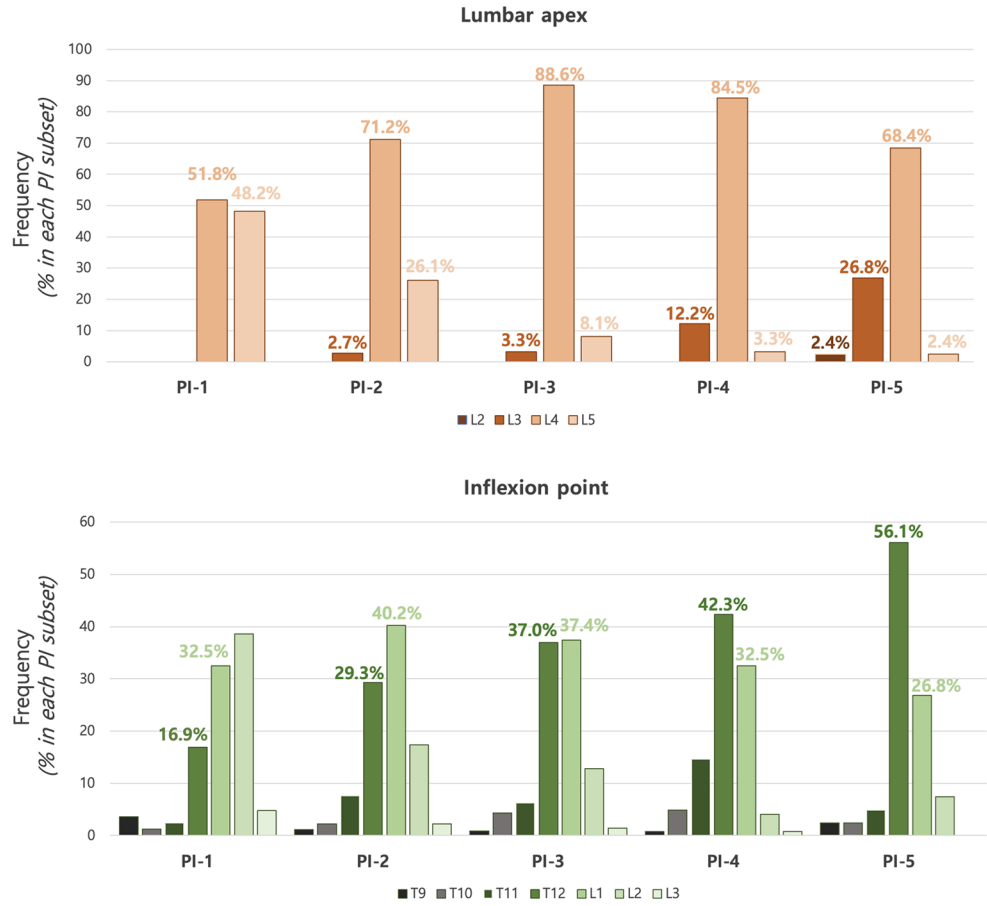
- **PT** =  $-12.7 + 0.38 \cdot \text{PI} + 0.14 \cdot \text{Age}$  ( $R^2 = 0.43$ , residual standard error: 5.1°).
- **TPA** =  $-16.9 + 0.34 \cdot \text{PI} + 0.15 \cdot \text{Age}$  ( $R^2 = 0.40$ , residual standard error: 5.1°).
- **SSA** =  $109.8 + 0.58 \cdot \text{PI} - 0.19 \cdot \text{Age}$  ( $R^2 = 0.49$ , residual standard error: 6.3°).
- **SFA** =  $173 + 0.39 \cdot \text{PI} + 0.11 \cdot \text{Age}$  ( $R^2 = 0.31$ , residual standard error: 6.2°).
- **LLmax** =  $-32 - 0.69 \cdot \text{PI} + 0.17 \cdot \text{Age}$  ( $R^2 = 0.40$ , residual standard error: 8.6°).

Residual standard errors increased between 0.3 and 0.8° if age was not taken into account. Regressions formulas were performed in each gender subset, exhibiting little difference

**Table 4** Normative values of lumbar lordosis for each PI group. Reference values are also given for each disc, vertebral body and regional angulation in the lumbar spine. Significant differences among groups are marked with a “\*” if *p-values* < 0.05, and with “†” if *p-value* < 0.001. PI groups are respectively: “very low” (PI < 39°), “low” (39°;47°), “average” (47°;55°), “high” (55°;63°), and “very high” (PI > 63°)

PI groups	PI-1 (<39°)	PI-2 (39–47°)	PI-3 (47–55°)	PI-4 (55–63°)	PI-5 (>63°)
n	83	184	211	123	41
† LLmax (°)	-47.7±9.3	-55.3±9.2	-59.4±9.0	-65.0±9.0	-72.0±10.8
† LLprox (°)	-21.3±7.2	-22.8±7.9	-23.5±5.9	-25.8±7.1	-25.7±8.1
† LLdist (°)	-26.4±7.8	-32.5±7.1	-35.9±6.8	-39.2±6.4	-46.3±8.0
† L1-S1 (°)	-45.0±9.7	-53.8±9.4	-58.1±9.1	-62.9±8.8	-70.5±11.5
† L1-L4 (°)	-12.4±6.8	-18.0±7.5	-21.5±7.0	-24.9±6.9	-28.6±8.5
† L4-S1 (°)	-32.5±7.4	-35.8±6.7	-36.6±7.1	-38.0±6.1	-42.0±8.6
<i>Disc angles</i>					
L5-S1 (°)	-11.8±5.8	-14.2±5.7	-13.3±6.0	-13.4±5.8	-13.3±7.5
* L4-L5 (°)	-11.1±3.1	-11.5±3.6	-11.5±3.5	-11.9±3.7	-13.2±5.1
† L3-L4 (°)	-8.8±2.7	-9.7±2.8	-10.4±3.0	-10.6±2.8	-12.4±3.3
† L2-L3 (°)	-6.8±2.7	-7.9±3.1	-8.5±2.6	-9.0±2.7	-9.5±2.7
† L1-L2 (°)	-3.8±3.0	-5.1±3.1	-6.0±2.9	-6.7±2.8	-6.3±2.7
† T12-L1 (°)	-2.9±2.4	-3.4±2.3	-3.5±2.4	-4.5±2.7	-3.8±2.5
T11-T12 (°)	-1.7±2.2	-1.6±2.2	-1.8±2.2	-1.9±2.8	-1.4±2.5
<i>Vertebral wedges</i>					
† L5 body (°)	-8.0±3.3	-8.1±3.2	-9.0±3.2	-9.3±3.4	-11.0±4.1
† L4 body (°)	-1.7±2.4	-2.0±2.9	-2.8±2.9	-3.4±2.8	-4.5±2.8
† L3 body (°)	-0.3±2.4	-0.7±2.6	-1.1±2.4	-1.5±2.5	-2.3±2.5
† L2 body (°)	2.5±2.7	1.6±2.6	1.1±2.2	0.3±2.2	-0.5±2.3
† L1 body (°)	4.8±2.9	3.8±2.7	3.3±2.6	2.7±2.4	2.3±1.9
* T12 body (°)	4.8±2.4	4.3±2.4	4.1±2.3	3.7±2.3	3.6±2.0
<i>Regional angulations</i>					
† L4-S1 (°)	-32.5±7.4	-35.8±6.7	-36.6±7.1	-38.0±6.1	-42.0±8.6
† L3-L5 (°)	-29.8±6.0	-32.0±6.6	-34.7±6.3	-36.8±6.5	-43.3±9.2
† L2-L4 (°)	-15.1±5.8	-18.7±6.5	-21.6±6.1	-24.2±6.3	-29.0±8.1
† L1-L3 (°)	-3.7±6.3	-8.3±6.8	-11.1±6.2	-14.3±6.0	-16.2±7.4
† T12-L2 (°)	5.3±7.1	1.3±6.2	-0.9±6.6	-4.6±5.9	-4.7±6.2
† T11-L1 (°)	9.0±6.3	7.3±6.3	6.7±6.2	4.2±6.6	4.9±5.7

**Fig. 4** Barplots representing lumbar apex and inflexion point locations in every PI group



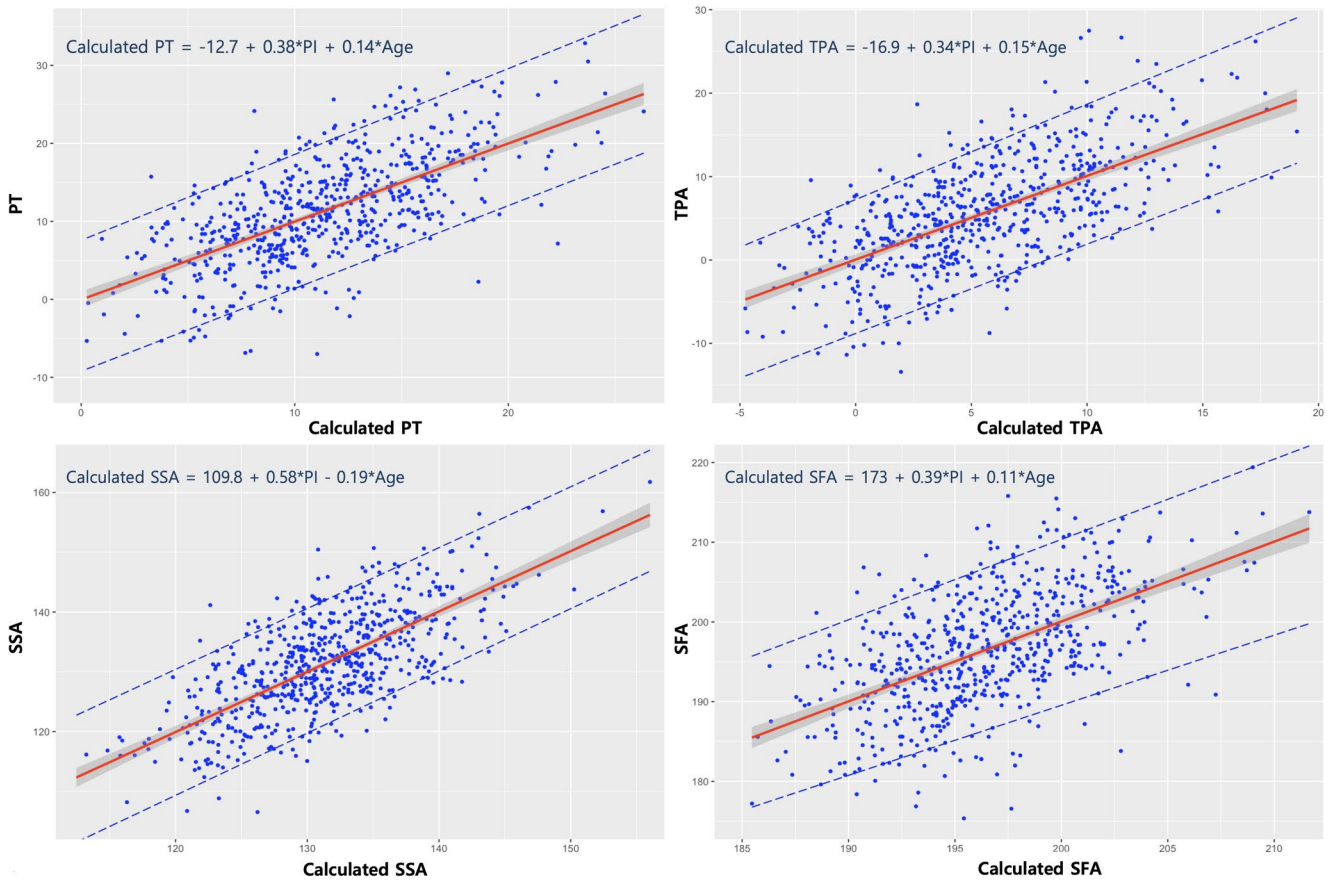
**Table 5** Regression models for males and females. *RSE = Residual standard error*

	Regression models	R <sup>2</sup>	RSE
<b>Males</b>			
Pelvic tilt	PT = -12.4 + 0.38*PI + 0.15*Age	0.40	4.9°
TPA	TPA = -17.0 + 0.36*PI + 0.16*Age	0.41	4.8°
SSA	SSA = 109.3 + 0.56*PI - 0.20*Age	0.51	5.9°
SFA	SFA = 173.9 + 0.37*PI + 0.11*Age	0.25	6.2°
LLmax	LLmax = -31.8 - 0.66*PI + 0.18*Age	0.38	8.4°
<b>Females</b>			
Pelvic tilt	PT = -13.4 + 0.38*PI + 0.14*Age	0.45	5.3°
TPA	TPA = -17.9 + 0.34*PI + 0.15*Age	0.44	5.1°
SSA	SSA = 111.5 + 0.58*PI - 0.20*Age	0.48	6.4°
SFA	SFA = 172.5 + 0.41*PI + 0.11*Age	0.36	6.2°
LLmax	LLmax = -32.9 - 0.69*PI + 0.17*Age	0.41	8.5°

(Table 5). Predicted values correlated with measured values at 0.7 for PT and SSA, 0.6 for TPA, SFA and LL max (*all p-values < 0.001*) (Fig. 5).

## Discussion

Understanding spinal curvatures and their influencing factors is necessary to decrease the high rate of mechanical complications associated with adult spinal deformity surgery. Another requirement is to define custom-made global alignment goals, personalized according to each patient's anatomy and age. The results of this study demonstrated that pelvic incidence was correlated with pelvic parameters and lumbar lordosis but not with the other spinal curvatures and lower limb parameters. Further, to our knowledge this is the first study in a large cohort of healthy volunteers demonstrating that TPA, SSA, SFA and pelvic tilt were correlated with PI and age, hence their values had to be interpreted according to these parameters. This study provided normative values for segmental, regional and global alignment across each PI subset and predictive formulas according to PI and age. These results are useful for alignment assessment and preoperative planning in the setting of adult spinal



**Fig. 5** Plots representing measured versus calculated values for PT, SFA, TPA and SFA

deformity surgery. Further, this is of particular interest as it has been demonstrated that intraoperative TPA measurement in prone position was strongly correlated with postoperative one in erect position [30]. Thus, the results of this study can help surgeons reach correction goal intraoperatively with patient-specific TPA.

The use of whole-body biplanar radiography has become essential to assess global alignment, as it presents several advantages to allow a more thorough alignment analysis. The first is that it provides full body radiograph whereas conventional radiography only captures a segment [31]. Hence, biplanar radiographs are not subject to stitching artifacts used in digital radiography to obtain full body films [32]. Lower limbs and cervical spine are major compensation mechanisms that can be recruited in case of sagittal malalignment [33]. While physiological spinal alignment has been extensively described in literature, studies considering the whole body remain scarce. Analyzing spinal alignment cannot be performed by overlooking lower limbs, or cervical spine. More, there is distortion due to diverging x-rays in standard cone beam conventional radiography [34], that may lead to measurement errors when analyzing lengths or angles [35, 36]. In biplanar radiography, horizontal distortion is

corrected in 3D calibrated space. The second advantage is the ability to perform 3D reconstructions thus allowing axial plane measurements. Last, the radiation exposure is significantly lower for patients, which is more acceptable when recruiting healthy volunteers [37].

In this study, the cohort was divided into five groups according to pelvic incidence. Lumbar apex and inflexion point locations significantly differed between groups, as they shifted cranially with increased PI. These results corroborate Roscop et al.'s conclusions [38]. As expected, the three pelvic parameters jointly increased along with PI groups, as well as LLmax and L1-S1 lordosis. Both distal and proximal lumbar lordosis increased with PI, with a greater variation in distal LL. Conversely, L4-S1 variation across PI groups was lesser than L1-L4 lordosis. These results are in line with Pesenti et al.'s conclusions that observed in 119 healthy volunteers significant correlation between PI and L1-L4 lordosis, whereas L4-S1 lordosis remained stable [39]. Interestingly, lower lumbar discs did not play a major role in PI increase while variation in disc lordosis from L3-L4 to T12-L1 was more pronounced. More, all lumbar vertebral bodies were more lordotic with increased PI, corroborating previous results [40].

This study provides normative values for each lumbar disc and vertebral body in every PI group, that can be used as reference for degenerative surgery when fusion is needed. Indeed, the International Spine Study Group emphasized the necessity to achieve short fusions with proper alignment as half of the deformity cases in their database resulted from previous undercorrected fusions in the lumbar spine [41]. More, regional angulations are provided for each PI group at every vertebral level. This data is useful when treating lumbar fractures, in order to indicate surgery and define correction goals [42]. Intervertebral angular measurements of the lumbar spine have been previously published, without taking PI into account [9]. In this study, significant differences in regional angulations between PI groups were noted, emphasizing the need to account for PI when treating lumbar fractures.

Thoracic kyphosis, cervical curvature and lower limb parameters (apart from SFA) were not correlated with pelvic incidence in this study. Hence, spinal shape cannot be defined solely based on pelvic parameters. Other factors must be identified and taken into account, such as age, sex, or body morphology [43, 44].

Sardar et al. also reported the absence of correlation between TK and PI, in a multi-ethnic normative study [45]. This can be explained by the fact that rib cage constraints mobility of thoracic spine, and their strong anatomical relationship leads to significant associations between rib cage and thoracic spine parameters [46]. These findings also corroborate Prost et al.'s results that previously described the T10-L1 segment as being constant regardless of age and pelvic incidence [10].

The other global alignment parameters studied, ODHA and T1SPi, did not exhibit significant variations across PI groups. These finding corroborates Amabile et al.'s conclusion, describing ODHA as an invariant parameter in asymptomatic adults [26].

## Limitations

This is a transversal study, which may limit the interpretation of aging on radiographic alignment parameters. Second, although satisfactory, correlations coefficients between measured and calculated values of TPA, SSA, SFA and PT did not exceed 0.7. More, residual standard errors of linear models were estimated around 5° for PT and TPA, up to 9° for LL max, and R<sup>2</sup> values ranged from 0.31 to 0.49, indicating that other variables must be taken into account to estimate more precisely the studied parameters [43, 44, 46]. Last, validating these regressions in an independent cohort would have enhanced the generalizability of the formulas.

## Conclusion

This study proposes a global alignment stratification based on 5 PI groups. SSA, PT, TPA and SFA must be assessed according to patient's PI. This study provides normative values for each PI group, and predictive formulas taking age and PI into account to plan surgical procedure. Reference values of segmental lordosis and regional angulations are given for every PI group, that can be used for traumatology or degenerative spine surgery.

Pelvic incidence is correlated with pelvic tilt, distal and proximal lumbar lordosis, but cannot be used to define thoracic and cervical curvatures. Further studies are needed to look for yet undetermined non-radiographic parameters influencing thoracic and cervical curvatures.

**Author contributions** CV, EF and WS supervised the study. OG, AA, WS, HJK and VL provided data. MK and CV performed the statistical analysis and drafted the manuscript. All authors reviewed the final version of the manuscript.

**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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