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ORIGINAL ARTICLE

Lumbar lordosis does not correlate with pelvic incidence in the cases with the lordosis apex located at L3 or above

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Abstract

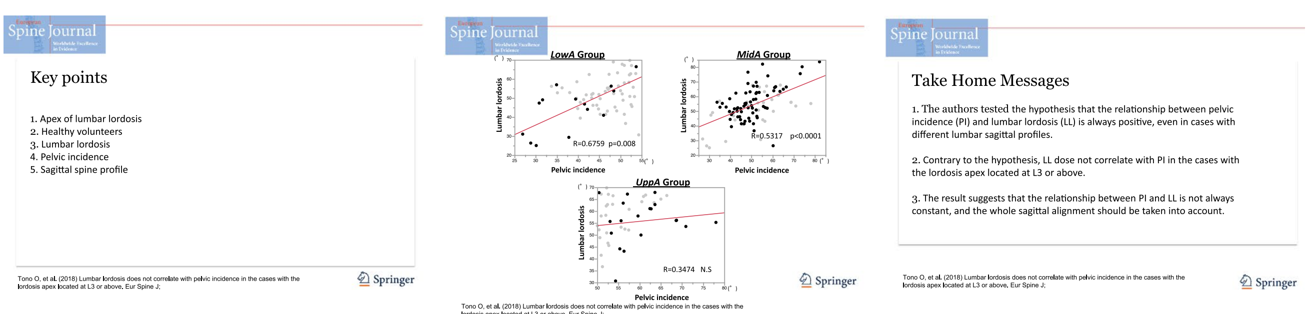
Purpose To test the hypothesis that the relationship between PI and L1–S1 lumbar lordosis (LL) is always positive, even in cases with different lumbar sagittal profiles.

Methods Standing whole-spine sagittal alignment was measured with EOS system in 100 healthy adults (46 men, 54 women, mean age 40.9 years). The apex of lumbar lordosis was defined as the most anterior lumbar vertebra or intervertebral disk from the gravity line determined by a force plate measurement. Subjects were stratified into three groups: the *upper* group with an apex between L1 and L3 (*UppA*, $n = 19$), the *middle* group with an apex from L3/4 to L4/5 (*MidA*, $n = 67$), and the *lower* group with an apex at L5 or below (*LowA*, $n = 14$). PI, PT, SS, thoracic kyphosis (TK), LL, SVA, T1 pelvic angle, and knee flexion angle were compared between the groups. The correlation between LL and PI in each group was also compared.

Results PI and SS differed significantly between the three groups, and LL was significantly different between *LowA* and *MidA* and *UppA*. TK and KF did not differ significantly between groups. LL and PI were significantly positively correlated in the *MidA* and *LowA* groups, but not in the *UppA* group.

Conclusion Contrary to the hypothesis, the correlation coefficient between PI and LL was not significant in the cases with apex above L3, suggesting that the relationship between PI and LL is not always constant, and whole sagittal alignment should be taken into account.

Graphical abstract These slides can be retrieved under Electronic Supplementary Material.



Keywords Apex of lumbar lordosis · Healthy volunteers · Lumbar lordosis · Pelvic incidence · Sagittal spine profile

Introduction

Deterioration of the sagittal alignment in the standing position impairs the health-related quality of life of patients with adult spinal deformity (ASD) [1]. The alignment also deteriorates with aging and kyphotic deformity, and therefore, the

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goal of surgical treatment for ASD is to achieve an optimal standing alignment, especially in the sagittal plane [2, 3]. It is difficult, however, to estimate the original spinal profile of a patient that already has a deformed spine.

Because L1–S1 lumber lordosis (LL) correlates with pelvic incidence (PI) [4, 5], a unique anatomic value for each individual, formulas to estimate a desirable LL according to the PI have been proposed [4–8]. Based on the basic relationship between PI and LL, Schwab et al. proposed that PI–LL mismatch is as an indicator for corrective surgery [3, 8, 9]. On the other hand, LL is a quantitative value of the angle at the level of the L1–S1 endplates, and patients with the same LL values may have a different sagittal lumbar profile [5, 10]. Roussouly et al. [10] reported that the apex of the LL moves cranially as the PI increases. In that study, however, a lateral radiograph of the spine and pelvis was made with the subject in a controlled standing position with their hands at rest [10]. Legaye et al. [11] evaluated the influence of the position of the arms on the location of the body's gravity line (GL) using a simple equation with a barycentremetric study and found that the variations in the location of the GL were proportionally connected to the changes in the sagittal position of the mass of the upper limbs induced by the various positions of the arms. Therefore, the relationship between the amount of lumbar lordosis and sagittal alignment remains unclear.

We established an alignment and balance measurement system using a 3D X-ray imager and simultaneous force plate and could determine the whole-body gravity line of the subject in standing posture with the hands on cheek and horizontal gaze [7]. In the present study, we hypothesized that there is constantly positive correlation between PI and LL even in the cases with different lumbar sagittal profiles, and the purpose of this study is to test the hypothesis using the measurement system.

Materials and methods

Following approval by the institutional review board, whole-body alignment in the standing position was measured using a slot-scanning X-ray imager (EOS system) in 100 healthy volunteers with no history of treatment for spine disease (46 men and 54 women) with a mean age of 40.9 years (20–70 years). Participants were instructed to stand on a force plate (GP Anima, Tokyo, Japan) installed at the center of the imager and place their line of sight on a horizontal gazing mirror, while placing their hands on their cheeks. The participants were scanned within 30 s from the skull to the feet at a speed of 7.6 cm/s, while also measuring the amount of body sway. The mean perpendicular line passing through the location of the center of gravity within a 30-s period was defined as the GL [7]. Subject health-related qualify of life was also evaluated using the Japanese version of the Oswestry Disability Index (ODI) [12]. The exclusion criteria of the study were as follows: lumbosacral transitional vertebrae (sacralized lumbar spine, lumbarized sacral vertebrae), 11 thoracic vertebrae, or scoliosis with a Cobb angle of 10° or more.

Radiologic measurements

We measured the PI, pelvic tilt (PT), sacral slope (SS), T1–T12 kyphosis (TK), LL, sagittal vertical axis (SVA), T1 pelvic angle (TPA) [13], and knee flexion angle (KFA) [14] (Fig. 1).

LL apex

Based on EOS imaging in the standing position, the cross-point of the intersection of the diagonal lines from the edges of each vertebral body was defined as the center of the vertebra (for S1, the center of the end plate was used), and the offset distance from the GL to the centrum of each vertebral body was measured (Fig. 2). The apex of LL was defined as the most anterior lumbar vertebra or intervertebral disk from the GL. If adjacent vertebral bodies had equal offset values, the level of the position of the intervertebral disk between the two vertebral bodies was considered to be the apex, e.g., when the values were equal for L3 and L4, the level of the L3/4 intervertebral disk was the apex. Participants were classified into three groups: the *upper* group (*UppA*) had an apex located between L1–L3, the *middle* group (*MidA*) had an apex located from L3/4 to L4/5, and the *lower* group (*LowA*) had an apex located at L5 or below.

Statistical analysis

The data are provided as the mean value and standard deviation unless otherwise indicated. All statistical analyses were carried out using the JMP Pro software package (version 11.0, SAS Institute, Cary, NC). A p value less than 0.05 was considered statistically significant. Because the data for the *MidA* group were not normally distributed, the Steel–Dwass test, a non-parametric multiple comparison test, was used for all pairwise comparisons between the groups. Power (1-β) and post hoc sample size for the statistical significance were also calculated.

The correlation analyses for PI and LL were performed using a linear regression analysis with Spearman's rank correlation coefficient.

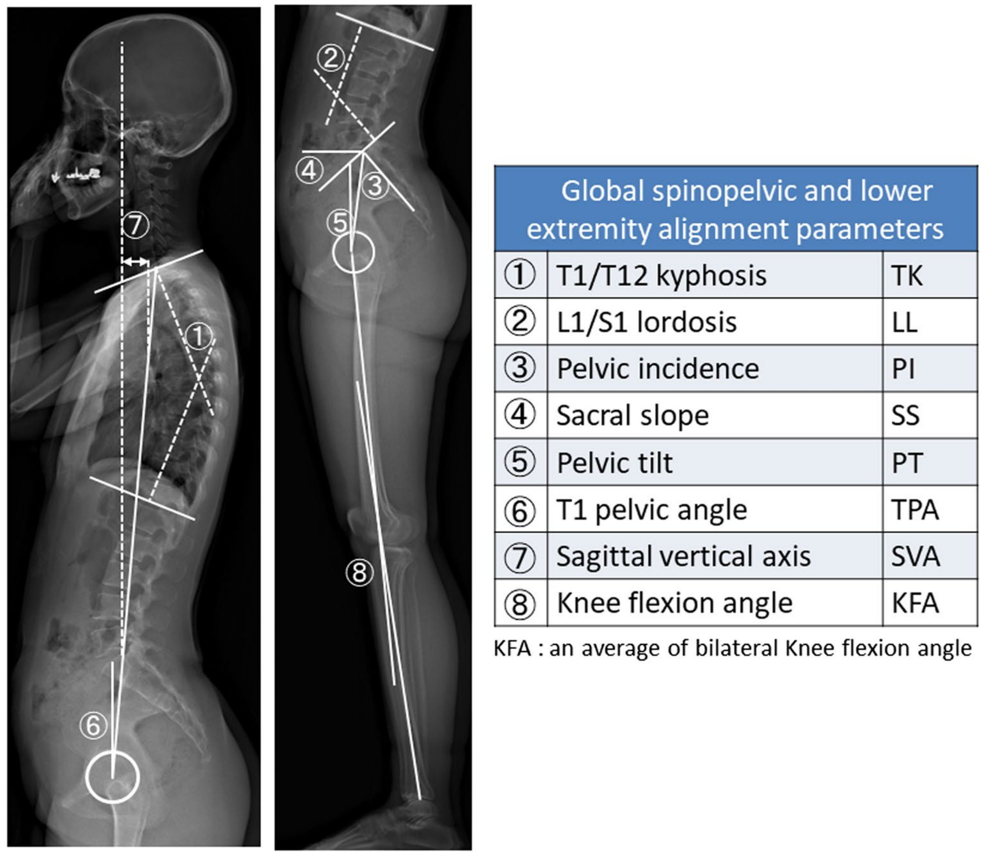

Fig. 1 Radiographic sagittal parameters in the standing position

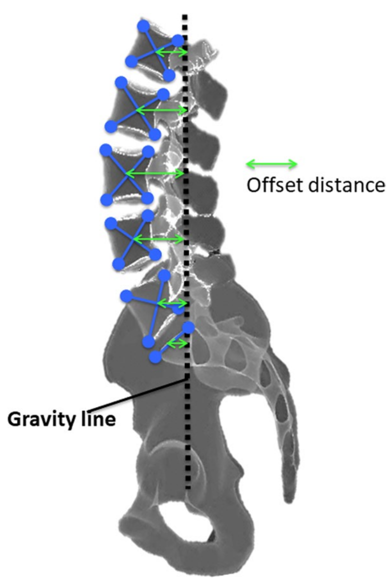

Fig. 2 LL Apex. Measurement of the offset distance between the center of the vertebra and the gravity line. The center of the vertebra is defined as the cross-point of the diagonal lines from the edges of the vertebral body. The LL apex was defined as the forefront lumbar vertebra or intervertebral disk from the GL

Table 1 Demographic and radiographic sagittal alignment data

	Mean	Minimum	Maximum	SD
Age (years)	40.9	20.0	70.0	12.2
BMI (kg/m^2)	21.9	16.9	34.6	2.9
ODI (%)	4.8	0.0	22.2	6.1
Pelvic incidence (°)	50.6	26.9	82.1	10.7
Pelvic tilt (°)	10.6	− 5.1	36.2	7.0
Sacral slope (°)	40.0	11.9	59.3	8.3
T1–12 kyphosis (°)	42.4	13.7	64.4	10.5
L1–S1 lumbar lordosis (°)	54.3	25.1	83.8	11.7
Sagittal vertical axis (cm)	− 0.1	− 4.1	7.5	2.4
T1 pelvic angle (°)	6.6	− 8.1	31.4	7.0
Knee flexion angle (°)	− 0.8	− 11.1	11.8	4.5

BMI body mass index, *ODI* Oswestry Disability Index

Results

Demographic parameters

The demographic data are provided in Table 1. The age distribution was as follows: 10 participants 20–30 years of age, 25 participants 30–40 years of age, 24 participants

40–50 years of age, 25 participants 50–60 years of age, and 16 participants 60–70 years of age. Mean body mass index was 21.9 ± 2.9 kg/m^2 (range, 16.9–34.6) and the mean ($\pm$ SD) ODI was $4.8 \pm 6.1\%$ (0–22.2%) (Table 1). The ODI was not significantly different between age groups (Spearman's rank correlation coefficient, $\rho = 0.180$, $p = 0.073$). Fairbank et al. [12] previously reported that the ODI is 10.2% in the normal population; thus, the mean value in our study can be considered normal.

The LL apex and radiographic parameters

Nineteen participants were classified as *UppA*, 67 as *MidA*, and 14 as *LowA*. PI and SS differed significantly between all groups. PT was significantly different between the *UppA* and *MidA,* and the *UppA* and *LowA* groups. LL was significantly different between the *MidA* and *LowA,* and the *UppA* and *LowA* groups. SVA was significantly different between the *UppA* and *LowA* groups. TPA was significantly different between the *UppA* and *MidA,* and the *UppA* and *LowA* groups. TK and KFA were not significantly different between groups (Tables 2, 3). In each comparison, power was sufficiently high except in TK and KFA. Post hoc significant sample size was almost satisfactory in all comparisons except in TK and KFA (Table 3).

Table 2 Sagittal alignment parameters (mean ± SD)

	UppA ($n = 19$)	*MidA* ($n = 67$)	*LowA* ($n = 14$)
PI	60.5 ± 7.16	50.3 ± 9.12	38.6 ± 8.4
PT	15.5 ± 6.94	9.7 ± 6.50	8.24 ± 6.6
SS	45.0 ± 8.62	40.6 ± 7.35	30.3 ± 8.6
TK	40.7 ± 11.13	42.7 ± 10.94	43.1 ± 7.2
LL	55.8 ± 9.35	55.9 ± 11.25	44.5 ± 12.6
SVA	1.4 ± 2.9	− 0.2 ± 2.2	− 1.3 ± 2.0
TPA	12.3 ± 7.81	5.6 ± 6.42	3.6 ± 4.3
KFA	− 0.04 ± 3.3	− 1.04 ± 4.92	− 0.89 ± 3.6

PI–LL correlation according to the location of the apex

LL and PI were significantly positively correlated for the *MidA* and *LowA* groups (*MidA* $r_s = 0.6759$, $p = 0.008$; *LowA* $r_s = 0.5317$, $p < 0.0001$), but they were not significantly correlated in the *UppA* group ($r_s = 0.3474$, $p = 0.5761$; Fig. 3).

Discussion

Humans accomplish standing upright position by regulated neuromuscular control of the base of the skeleton. To achieve a horizontal gaze, the human skeleton in the standing position is thought to function like a 'reverse pendulum.' The axial skeleton, the chain of balance, should be aligned under the balance of the 'cone of economy,' representing the perfect balance requiring a minimum of muscle activity used for postural maintenance in normal situations [15]. Regarding the sagittal whole-spine alignment in the standing posture, however, Stagnara [16] previously showed that the sagittal alignment has a wide range of variation in healthy subjects, and Bernhardt [17] also reported a large normal range for the sagittal alignment of the spine. Roussouly [10] evaluated the spinopelvic alignment in healthy subjects and classified it into four different types based on the degree of the SS, vertical location of the apex of the LL, and inclination angle of the LL. In healthy subjects, SS is strongly dependent on PI [5, 10]. Thus, the findings show that when PI is larger, the apex of LL is located more on the cranial side [10, 18]. Lumbar lordosis is not shaped as a concentric circle [19], and the majority of the lordotic portion comprises the lower part below L4 [20]. In Roussouly's classification, as the LL

Table 3 Comparison of the sagittal alignment parameters between groups according to the location of the apex LL

	UppA–MidA	*MidA–LowA*	*UppA–LowA*	Power ($1-\beta$)	Post hoc sample size
PI	< 0.0001***	0.0003**	< 0.0001***	1.00	15.04
PT	0.0019*	NS	0.0192*	0.91	47.47
SS	0.0181*	0.0004**	< 0.0001***	1.00	20.36
TK	NS	NS	NS	0.09	1052.12
LL	NS	0.0162*	0.0225*	0.89	50.81
SVA	NS	NS	0.0182*	0.87	53.46
TPA	0.0020*	NS	0.0014*	0.98	34.01
KFA	NS	NS	NS	0.11	827.53

Type I error (α), power ($1-\beta$), and post hoc significant sample size

UppA an apex of lumbar lordosis located between L1 and L3, *MidA* an apex of lumbar lordosis located from L3/4 to L4/5, *LowA* an apex of lumbar lordosis located at L5 or below

p value (*$p < 0.05$; **$p < 0.001$; ***$p < 0.0001$)

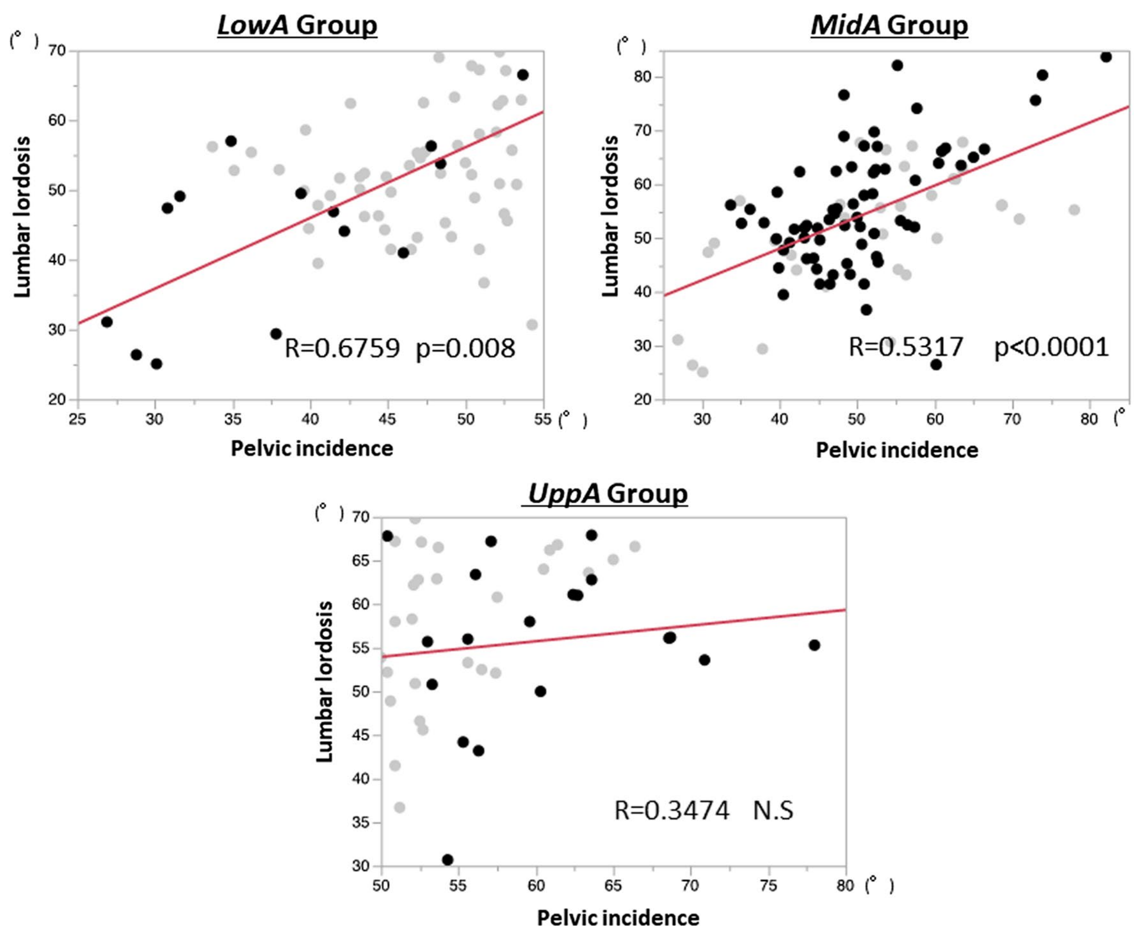

Fig. 3 PI–LL correlation according to the location of the apex

is divided into the upper and lower arcs with the apex as the boundary, the PI is small and a small SS is formed, the lower arc is smaller, and, as a whole, an LL with a small arc is formed [10]. Conversely, when PI is large, a large SS is formed and the lower arc becomes larger, which forms an arc with a large LL and a high-positioned apex [10].

In the present study, we further investigated the relationship between pelvic alignment and the shape of LL by defining the apex based on the GL of the whole body using a force plate synchronized with EOS imaging [7]. We examined the correlation between PI and LL in three groups that were stratified according to the vertical location of the apical vertebra. The findings showed that when the apex was located at L4 or below, LL and PI were positively correlated, whereas, when the apex was located at L3 or above, they were not correlated (Fig. 3). Thus, when the apex was located at L3 or above, the LL was not defined by PI. When PI was large, the inflexion point that served as the transition between lumbar lordosis and TK moved cranially [10], and the upper margin of the lumbar lordosis was located cranial to L1. Because LL is the numerical value of the angle formed by the endplate between L1 and the sacrum, the actual profile of the lumbar lordosis may be underestimated and it is speculated that this variation contributed to the loss of the correlation between PI and LL when the apex of lumbar lordosis was at L3 or higher.

When considering reconstructive surgery for ASD, LL is the directly correctable parameter; thus, various formulas for determining the optimal LL have been proposed [4, 7, 8]. In the formulas, LL is evaluated as a single quantitative value, and the overall shape of LL is not taken into consideration. In the SRS-Schwab classification that is widely used in the treatment of ASD, the PI–LL value is a sagittal plane modifier that has been shown to be associated with postoperative outcomes [9]. Postoperative implant failure has, however, been reported in more than one-third of cases when the SRS-Schwab classification was used while aiming for the target value [21, 22]. According to a recent report by the European Spine Study Group (ESSG), an uneven distribution of lordosis might be the cause of the mechanical complications. ESSG stated that this point of view has not been considered, and there are some inherent disadvantages to the modifications based on the SRS-Schwab classification. Thus, ESSG proposed scoring the spinopelvic alignment based on PI and calculated the proportion of L4–S1 lordosis for the entire LL as the lordosis distribution index considering the overall morphological evaluation of LL [23]. In a study reported by Anwar et al. [24], evaluations were carried out by calculating the sum of angles for each intervertebral segment, and the findings showed that as PI increases, the proportion attributable to the segment on the cranial side also increases and regulates the whole LL.

From the results of our study as well, the findings suggest that depending on the location of the apex, the relationship between PI and LL is different, which is contrary to our hypothesis. When the apex of LL was located at L3 or above, the correlation between LL and PI was lost and a formula based on PI–LL was not applicable. Thus, the target of correction is expected to be different depending on the lumbar sagittal profile. We suppose, for example, that when the location of the apex is at L4 or below (*MidA or LowA)*, it is necessary to form short or moderate lordosis according to the PI. In contrast, when the location of apex is at L3 or above (*UppA)*, it is necessary to form a long lordosis.

PI is an anatomic parameter that was established in the growth process of humans acquiring the ability to stand upright [25] and walk, and it is a key component of balance and global alignment required for a standing posture [4, 5, 26]. TK and the alignment between the hip joint, knee joints, and ankle joints are also determined by LL adapted to PI [14], as well as the major principle of the standing posture according to which a small LL is formed with a small PI, and a large LL is formed with a large PI [5, 20, 26]. We used EOS imaging to evaluate sagittal whole-body alignment in the standing posture and elucidated the impact of compensation by the lower extremities, including the KFA. We previously calculated the correlation between age and the SVA and KFA values, and our findings were as follows: SVA ($\rho = 0.3982$, $p < 0.0001$) and KFA ($\rho = 0.2302$, $p = 0.0212$) [14]. The findings in healthy individuals have also shown that the global alignment deteriorates with age and is compensated by the pelvis and the lower extremities, suggesting the importance of evaluating the sagittal profile of the whole body.

One limitation of this study was that it was carried out on individuals with a wide age range, namely from individuals in their 20s to individuals in their 70s, and as a result, age-related changes may have affected spinal alignment in some cases. Our previous study with 136 healthy subjects, however, showed that there was no statistically significant correlation between age and LL [14]. Thus, we consider that the age-related effect to the spinal alignment in healthy adults is minimal and believe that the present results were justified. On the other hand, it is also an advantage of this study to target healthy subjects in a wide age range. It is suggested that PI may increase with aging [27]. In each individual, the optimal LL varies with aging, so that it is possible to generalize the spinopelvic alignment by targeting a wide age range in healthy individuals. Future studies will assess therapeutic approaches for elderly patients with ASD by adding longitudinal evaluations based on the sagittal spinopelvic alignment of healthy adults.

Conclusion

Sagittal spinopelvic alignment differed according to the location of the LL apex, even in the cases with the same LL value. The correlation between PI and LL was stronger when the apex was located low on the spine, and PI was not correlated with LL when the apex was located at L3 or above. The results suggest that the relationship between PI and LL is not constant throughout the spine, and entire sagittal alignment should be taken into account.

Compliance with ethical standards

Conflict of interest None of the authors has received any grant or financial support for the present study.

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