Journal of Orthopaedic Science 27 (2022) 101–107

Contents lists available at ScienceDirect

Journal of Orthopaedic Science

journal homepage: http://www.elsevier.com/locate/jos

Original Article

Predictive formulae of ideal lumbar lordosis determined by individual pelvic incidence and thoracic kyphosis in asymptomatic adults

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ARTICLE INFO

Article history:
Received 16 October 2020
Received in revised form
20 November 2020
Accepted 30 November 2020
Available online 5 January 2021

ABSTRACT

Background: The precise prediction of ideal lumbar lordosis (LL) has become increasingly important in clinical practice. The aim of this study was to explore the regulatory mechanisms of sagittal spinopelvic alignment and to predict ideal LL based on individual pelvic incidence (PI) and thoracic kyphosis (TK) parameters in asymptomatic adults.

Methods: A total of 233 asymptomatic subjects older than 18 years were consecutively enrolled in our study between April 2017 and December 2019. A full-spine, standing X-ray was performed for each subject. The following parameters were measured in the sagittal plane: the apex of lumbar lordosis (LLA), the distance between the plumb line of the lumbar apex (LAPL) and the gravity plumb line, the inflection point (IP), LL, the upper arc and lower arc of lumbar lordosis (LLUA and LLLA, respectively), PI and TK. Stepwise multiple linear regressions were conducted, and the statistical significance level was $P < 0.05$.

Results: Both PI and TK were two important predictive variables for LLA, LAPL, IP and LL. In addition, the LLUA was mainly explained by TK, while the LLLA was explained by PI. The corresponding predictive models are listed as follows: LLA = 17.110 − 0.040*PI + 0.023*TK (R^2 = 0.380), LAPL = 31.296 + 0.467*PI − 0.126*TK (R^2 = 0.309), IP = 10.437 + 0.091*TK − 0.029*PI (R^2 = 0.227), LL = 2.035 + 0.618*PI + 0.430*TK (R^2 = 0.595), LLUA = 0.893 + 0.418*TK (R^2 = 0.598), LLLA = 3.543 + 0.576*PI (R^2 = 0.433).

Conclusion: The specific sagittal lumbar profile should be regulated by both pelvic and thoracic morphology. Such predictive models for lumbar parameters determined by individual PI and TK parameters have been established, which are meaningful for surgeons to better understand the regulatory mechanisms of sagittal spinopelvic alignment and reconstruct a satisfactory lumbar alignment.

1. Introduction

It is commonly accepted that sagittal spinopelvic balance is of prime importance for a great quality of life [1,2]. Among various regulatory mechanisms, modification of lumbar lordosis (LL) plays a major role in the maintenance of a well-balanced alignment of the sagittal plane [3–5]. Most surgical corrections for adult spinal deformity (ASD) diseases involve the fusion and reconstruction of lumbar segments, and acquisition of physiological lumbar alignment has been testified to remarkably reduce the occurrence of mechanical complications suffered after ASD surgery [6–8]. Therefore, the precise prediction of ideal LL has become increasingly important in clinical practice.

First, many researchers believe that pelvic morphology, defined by pelvic incidence (PI), is a primary driver of lumbar alignment regulation [9,10]. Accordingly, Roussouly and colleagues [4] described four disparate types of lumbar alignment in light of the sacrum orientation and PI in a normal adult population; however, why a low PI or sacral slope (SS) is associated with two diverse kinds of lumbar shapes, type 1 (significant kyphosis and short lordosis) and type 2 (hypokyphosis and hypolordosis), remains in doubt (Figs. 1 and 2). In addition, some researchers tried to build a series of algorithms that inferred LL simply from PI, such as LL = 0.67*PI + 23.7 [1] and LL < PI ± 10° [11]; however, Sebaaly et al. [7] and Rose et al. [11] found that the above models failed to decrease the rate of mechanical complications or obtain a balanced sagittal alignment after ASD surgery. In contrast, they both acknowledged that the formula

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https://doi.org/10.1016/j.jos.2020.11.022
0949-2658/

with a combination of PI and thoracic kyphosis (TK), LL < 45°-TK-PI, would be more beneficial for improving surgical outcomes [7,11]. Moreover, a close correlation between TK and LL has also been largely reported in the literature [12,13].

The aforementioned evidence illustrates that the effect of TK on LL is indispensable. Therefore, it may be speculated that the lumbar spine needs to adjust its own sequence to concurrently match not only PI but also TK; on the other hand, surgeons should create optimal lumbar alignment to adapt these two structural components together during corrective operations [11,13]. However, most previous studies exclusively take into account the influence of PI and ignore the effect of TK when analysing lumbar alignment [9,10,14]; as a result, the efficacies of these pre-existing formulae are likely questionable. Recently, Pan et al. [13,14] published two papers that separately elucidated the reciprocal relationships of lumbar alignment with pelvic and thoracic morphology. On this basis, we aimed to further investigate the regulatory mechanisms within sagittal spinopelvic alignment and to forecast the theoretical values of lumbar parameters, comprehensively incorporating the impacts of PI and TK, by means of multiple linear regressions in asymptomatic adults.

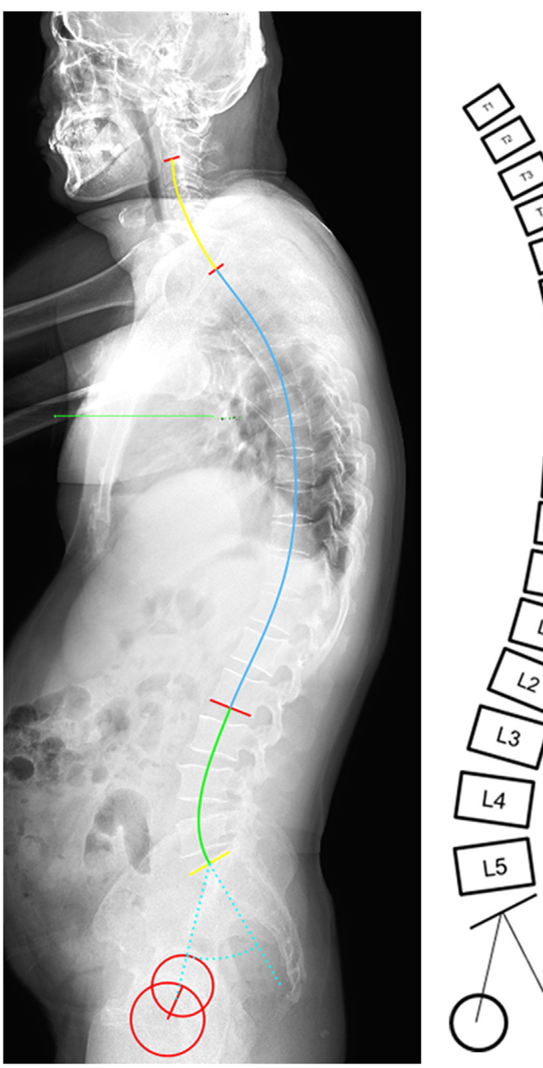

Fig. 1. Roussouly type 1, a low sacral slope (30.3°) or pelvic incidence (44.1°) with a large thoracic kyphosis (55.9°); the apex of lumbar lordosis at L4/5, inflection point at L2, lumbar lordosis = 51.9°, the upper arc of lumbar lordosis = 21.6°, the lower arc of lumbar lordosis = 30.3°.

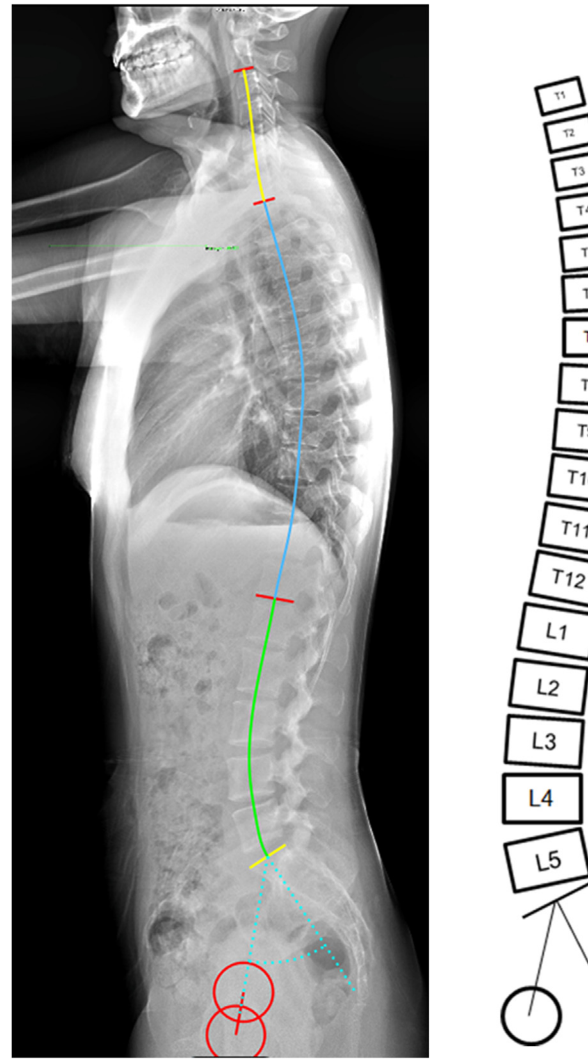

Fig. 2. Roussouly type 2, a low sacral slope (32.9°) or pelvic incidence (44.0°) with a small thoracic kyphosis (27.2°); the apex of lumbar lordosis at L4, inflection point at T12, lumbar lordosis = 45.4°, the upper arc of lumbar lordosis = 12.5°, the lower arc of lumbar lordosis = 32.9°.

2. Materials and methods

2.1. Study population

A total of 256 asymptomatic subjects aged 18 years or older were consecutively enrolled in our study between April 2017 and December 2019. The entire subjects were Chinese, and they were mainly consisted of medical students, physicians, nurses and other volunteers who participated in a health screening program. Informed consent was obtained from each individual who participated in this study, and ethical approval was provided by the institutional review board. Full-spine X-rays were collected for the assessment of spinopelvic parameters from all subjects in an erectly standing posture with a 90° position (the arms straight out, elbows extended and hands gently grasping a pole) or clavicle position (the elbows fully flexed and hand placed into the supraclavicular fossae) [15]. The exclusion criteria were (1) a lumbar- or thoracic-specific disease, (2) hip joint or pelvic disease and (3) neurological or neuromuscular disease. To ensure a "balanced" sagittal alignment, films with a sagittal vertical axis (SVA, the horizontal distance from the C7 plumb line to the posterior corner of the sacrum) larger than 50 mm were also excluded [2].

Among the enrolled individuals, 23 subjects were excluded (13 with unclear anatomical structure in radiographic films, 5 with spinal scoliosis over 10° in coronal plane, 3 with lumbar spondylolisthesis and 2 with vertebral dysplasia). Finally, 233 subjects, consisting of 105 females and 128 males (sex ratio ≈ 0.8:1), were included in the current study. The average age of the subjects was 47.5 ± 14.9 years, with a span of 18–72 years, and the stratification of individuals on the basis of age was as follows: 34 (14.6%, 10 women and 24 men) aged <30 years, 32 (13.7%, 12 women and 20 men) in their 30s, 48 (20.6%, 22 women and 26 men) in their 40s, 55 (23.6%, 28 women and 27 men) in their 50s and 64 (27.5%, 33 women and 31 men) aged ≥60 years.

2.2. Radiographic measurements

First, vertebrae from T1 to L5 were assigned numbers from 1 to 17 to simplify data collection and analysis [13]. Namely, larger vertebral numbers were correlated with lower levels. When the point was located at a disc between two vertebrae, a value of 0.5 was added to the superior vertebra number. For instance, when the point was located at the vertebra T12, the value was recorded as "12"; and when the point was located at the disc between T12 and L1, the value was recorded as "12.5". Next, the apex of lumbar lordosis (LLA), defined as the most anterior lumbar vertebra or disc touching the vertical line, was documented [4]. Furthermore, the distance parameter of the sagittal vertical axis was measured as the horizontal offset from the plumb line of the lumbar apex (LAPL) to that of the posterosuperior corner of the sacrum [14]. Additionally, the inflection point (IP), corresponding to the most tilted vertebra at the transition from kyphosis to lordosis, also needed to be recorded [4]. In terms of the angular parameters, LL bounded by the IP and the superior endplate of S1, TK bounded by the first thoracic vertebra and the IP, and PI were all identified from each lateral radiograph. Furthermore, to better depict lumbar curvature, LL was divided into two arcs of a lordotic circle, the upper arc and the lower arc of lumbar lordosis (LLUA and LLLA) above and below the LLA [14]. The above radiographic parameters are further elaborated in a graphic manner (Fig. 3).

2.3. Statistical analysis

The data were analysed using SPSS 17.0 statistics software (SPSS Inc., Chicago, IL, USA). Descriptive statistics are listed as the mean and standard deviation (SD). The data mentioned above were cautiously assessed twice by one experienced clinician, and the average value was calculated as the final result. The correlation analysis between PI and TK was performed using the Spearman correlation coefficient since PI didn't follow a normal distribution in this study. Moreover, stepwise multiple linear regressions were conducted to calculate lumbar parameters as a function of PI and TK values, and R^2 was used to estimate the explanatory power of the models. Furthermore, post hoc power analysis was performed using G*Power Analysis software version 3.1.9.7 (Universität Kiel, Germany). Statistical significance was indicated by $P < 0.05$.

3. Results

Table 1 shows the descriptive statistics and the ranges of the radiographic data involved in this study. In addition, a weak correlation was found between TK and PI ($r_s = 0.177$, $P = 0.007$). The consequences of multiple linear regressions are displayed in detail in Table 2. As shown in our results, both PI and TK were two important predictors for LLA, LAPL, IP and LL; besides, LLUA was mainly explained by TK, while LLLA was explained by PI. The corresponding predictive models are listed as follows:

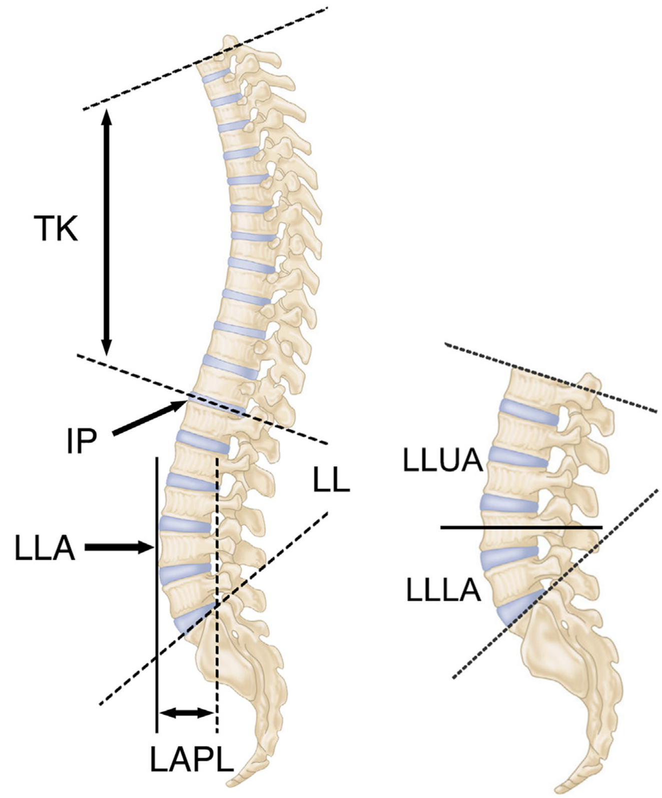

Fig. 3. Descriptions of sagittal parameters. TK, thoracic kyphosis; IP, inflection point; LLA, apex of lumbar lordosis; LAPL, plumb lines of lumbar apex; LL, lumbar lordosis; LLUA, upper arc of lumbar lordosis; LLLA, lower arc of lumbar lordosis.

$LLA = 17.110 - 0.040{*}PI + 0.023{*}TK$ ($R^2 = 0.380$)
$LAPL = 31.296 + 0.467{*}PI - 0.126{*}TK$ ($R^2 = 0.309$)
$IP = 10.437 + 0.091{*}TK - 0.029{*}PI$ ($R^2 = 0.227$)
$LL = 2.035 + 0.618{*}PI + 0.430{*}TK$ ($R^2 = 0.595$)
$LLUA = 0.893 + 0.418{*}TK$ ($R^2 = 0.598$)
$LLLA = 3.543 + 0.576{*}PI$ ($R^2 = 0.433$)

The post hoc power analysis demonstrated that our tests were overpowered; with an alpha set at 0.05, all multiple linear regressions achieved a power of 1.

4. Discussion

Human lumbar lordosis, a unique structure that is not detected in other species, is dedicated to an erect posture and bipedal locomotion for a long duration [16]. Based on analysis of abundant normal sagittal profiles, Roussouly et al. [4] proposed four

Table 1
Descriptive statistics of radiographic parameters.

Sagittal parameters	Mean	Standard deviation	Minimum	Maximum
LLA	16.1	0.7	12.5	17.5
LAPL (mm)	48.8	8.2	31.3	86.4
IP	12.3	2.1	7.0	16.0
LL (°)	46.3	11.0	10.2	74.8
LLUA (°)	15.7	6.0	3.0	33.4
LLLA (°)	30.7	8.7	6.9	53.9
PI (°)	47.1	9.9	23.2	80.1
TK (°)	35.4	11.1	9.6	68.3

LLA, apex of lumbar lordosis; LAPL, plumb lines of lumbar apex; IP, inflection point; LL, lumbar lordosis; LLUA, upper arc of lumbar lordosis; LLLA, lower arc of lumbar lordosis; PI, pelvic incidence; TK, thoracic kyphosis.

Table 2
Stepwise multiple linear regressions.

Lumbar parameters	Variables	B	Standard error	t	P	R^2
LLA	Constant	17.110	0.194	88.233	<0.001	0.380
	PI (°)	−0.040	0.004	−10.736	<0.001	
	TK (°)	0.023	0.003	7.022	<0.001	
LAPL (mm)	Constant	31.296	2.424	12.909	<0.001	0.309
	PI (°)	0.467	0.046	10.077	<0.001	
	TK (°)	−0.126	0.041	−3.050	0.003	
IP	Constant	10.437	0.650	16.069	<0.001	0.227
	TK (°)	0.091	0.011	8.184	<0.001	
	PI (°)	−0.029	0.012	−2.305	0.022	
LL (°)	Constant	2.035	2.472	0.823	0.411	0.595
	PI (°)	0.618	0.047	13.080	<0.001	
	TK (°)	0.430	0.042	10.196	<0.001	
LLUA (°)	Constant	0.893	0.836	1.068	0.287	0.598
	TK (°)	0.418	0.023	18.520	<0.001	
LLLA (°)	Constant	3.543	2.087	1.697	0.091	0.433
	PI (°)	0.576	0.043	13.277	<0.001	

LLA, apex of lumbar lordosis; PI, pelvic incidence; TK, thoracic kyphosis; LAPL, plumb lines of lumbar apex; IP, inflection point; LL, lumbar lordosis; LLUA, upper arc of lumbar lordosis; LLLA, lower arc of lumbar lordosis.

characteristic types of lumbar lordosis, as categorized by a sequence of radiographic parameters, including SS, PI, LLA, IP, LLUA and LLLA, and they suggested that a primary target of surgical intervention for patients with ASD diseases was to establish their original physiological alignment, in particular, lumbar alignment, fall into one of four types [6,17]. Numerous previous studies have demonstrated the prominent advantages of Roussouly classification in preventing postoperative mechanical issues in ASD surgery [6–8]. For example, Sebaaly et al. [6] pointed out that postoperative Roussouly type matching (22.5% vs. 46.8%, $P < 0.001$) could significantly decrease the rate of mechanically related complications. Even so, there are still some defects in Roussouly classification. For instance, it offers only qualitative descriptions of lumbar shapes, such as hypolordosis and hyperlordosis, instead of specific values of lumbar parameters that can be more helpful to estimate the magnitude of corrections needed for patients with spinal deformity; furthermore, the effect of TK is also neglected in types 3 and 4 (Figs. 4 and 5).

To date, numerous studies have consolidated our concept that LL should be simultaneously adjusted by PI and TK [3–5,11–14]. Sacral and thoracic kyphosis first form in utero, and the lumbar segments then progressively generate the corresponding lordosis in an attempt to adapt the thoracic and pelvic configurations for upright standing [13,18,19]. Therefore, it is reasonable to model the sagittal profile of the lumbar spine determined by individual TK and PI parameters. Preliminary observation revealed substantial individual variability in TK (from 9.6° to 68.3°) and PI (from 23.2° to 80.1°), causing a variety of lumbar curves, reflected in a broad spectrum of not only angular but also geometric parameters, across the normal population. Theoretically, the thoracic spine and pelvis can be regarded as growing independently since they have separate morphologies due to rib cage and pelvic cavity development rather than for an erect gesture [18,19]; some previous studies also indicated no association between TK and PI [1,20,21]. Nevertheless, in this paper, the authors found a weak link between TK and PI ($r_s = 0.177$, $P = 0.007$), indicating that a more or less indirect interaction might be yielded among PI and TK by virtue of a bridging function of the lumbar spine; however, the effect appears to be relatively unapparent in general.

In the present study, a number of geometric parameters were employed to exactly describe the features of the lumbar contour, which possess more advantages over conventional angular

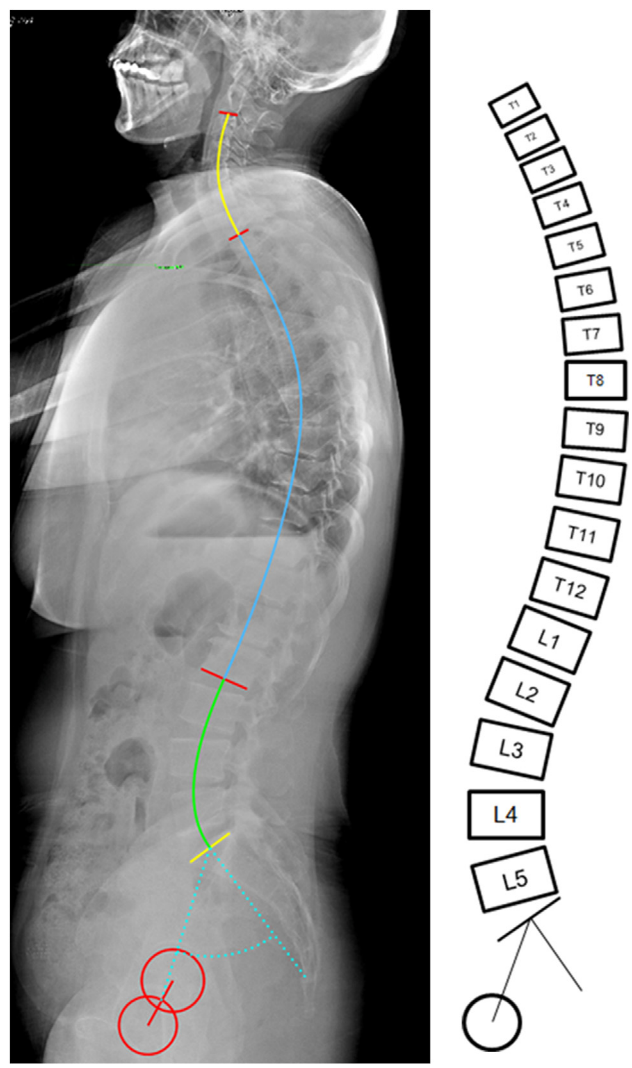

Fig. 4. Roussouly type 3, a moderate sacral slope (36.4°) or pelvic incidence (54.1°) with a large thoracic kyphosis (52.3°); the apex of lumbar lordosis at L4, inflection point at L2, lumbar lordosis = 57.1°, the upper arc of lumbar lordosis = 20.7°, the lower arc of lumbar lordosis = 36.4°.

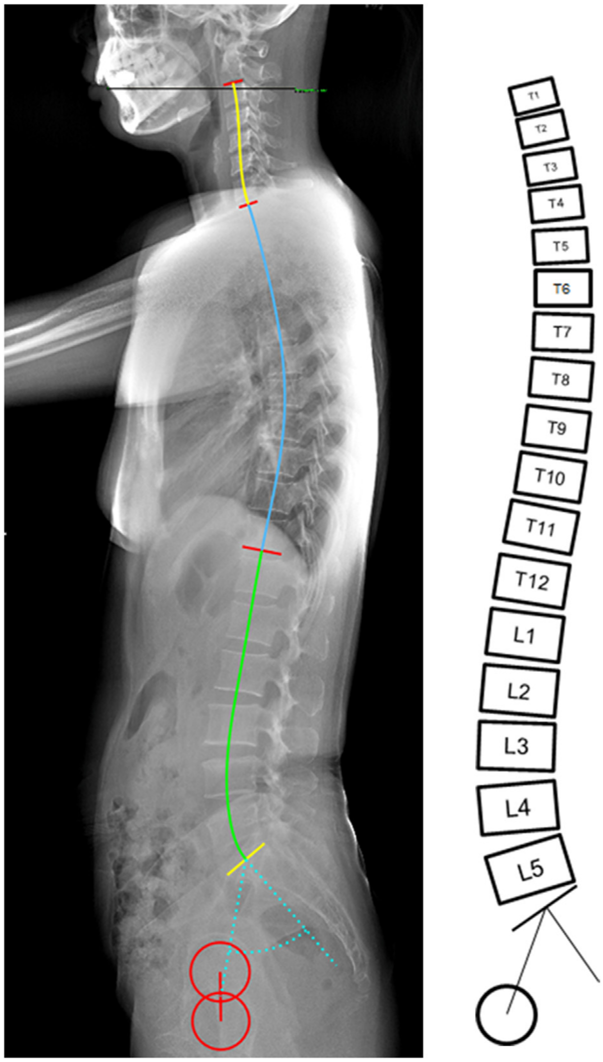

Fig. 5. Roussouly type 3, a moderate sacral slope (40.4°) or pelvic incidence (50.9°) with a small thoracic kyphosis (29.3°); the apex of lumbar lordosis at L3/4, inflection point at T11, lumbar lordosis = 49.1°, the upper arc of lumbar lordosis = 8.7°, the lower arc of lumbar lordosis = 40.4°.

parameters [4,13,14,20]. The LLA, to some extent, is capable of representing the sagittal lumbar profile [14], and Sebaaly et al. [7] reported that restoring the LLA back to its initial location could notably diminish the incidence of proximal junctional kyphosis (PJK) to 13.5%, compared to 38.9% in the other group ($P = 0.01$), with an odds ratio of 4.6. In this paper, the location of the lumbar apex was substantiated by two geometric parameters, the longitudinal vertebral level (LLA) and its horizontal distance relative to the gravity line (LAPL) [14]. The LLA and LAPL were dominated by both PI ($B = -0.040$, $P < 0.001$ and $B = 0.467$, $P < 0.001$, respectively) and TK ($B = 0.023$, $P < 0.001$ and $B = -0.126$, $P = 0.003$, respectively). Namely, a larger PI or smaller TK was correlated with the LLA being positioned more cranially and farther away from the gravity line and vice versa. The results can be manifested in the Roussouly classification [4]. For example, as PI or SS augments from type 1 to type 4, the LLA will gradually move superiorly; in addition, the thoracic spine presents hyperkyphosis in type 1 compared with type 2, and the level of the LLA in type 1 (mean middle L5) is thus lower than that in type 2 (mean base L4), which could account for why a similar PI or SS is accompanied by two different patterns of the lumbar spine. Hence, surgeons should choose a correct position of the LLA via the individual PI and TK values in the setting of spinal reconstruction.

The IP can determine the amount of vertebrae involved in the kyphotic or lordotic curves and is therefore deemed an important parameter to assess sagittal spinal alignment [13]. In this paper, akin to the LLA, both TK ($B = 0.091$, $P < 0.001$) and PI ($B = -0.029$, $P = 0.022$) contributed to the IP model as two independent variables. Accordingly, a large PI or flat TK is associated with a high IP level or an extension of the lordotic span into the thoracolumbar junction, which is in agreement with several past publications [4,5,13]. First, a positive association between IP and TK ($r_s = 0.391$, $P < 0.001$) was evidenced by Pan et al. [13], while a negative link between IP and PI ($r = -0.28$, $P < 0.001$) was evidenced by Roussouly et al. [4]. Next, in the Roussouly classification [4], because TK is greater in type 1 than in type 2, descending the level of the IP, the vertebrae constituting the lordosis are thus smaller in type 1 (average of 4 vertebrae) than in type 2 (average of 5 vertebrae). In addition, along with the increase in PI or SS from type 1 to type 4, the IP continuously shifts upwards, inducing more vertebrae included in the lordosis. Hey et al. [22] also affirmed the definite impacts of TK on the IP and LLA from another approach, and they found that natural and relaxed standing, parallel to an aged spine, could lead to a more kyphotic appearance with concomitant lower levels of the IP and LLA compared with directed standing for an identical individual. Furthermore, it should also be noted that, as exhibited in our results, TK ($B = 0.091$, $P < 0.001$) could have a greater impact on the IP than PI ($B = -0.029$, $P = 0.022$); therefore, selection of an adequate IP should depend principally on TK and secondarily on PI when designing the surgical strategy.

To appraise the curvature of LL, angular parameters were also applied in this study. Our findings suggested that LL was concurrently dictated by PI ($B = 0.618$, $P < 0.001$) as well as TK ($B = 0.430$, $P < 0.001$); in other words, a large PI or TK necessitates a hyperextension of lordosis to match the inferior pelvic and superior thoracic morphologies. Additionally, the predictive ability ($R^2 = 0.595$) of the LL model, illustrating that 59.5% of the total variance observed with LL could be explained by PI and TK, is stronger than that of earlier models that merely contained a single variable, such as $LL = 0.888*PI - 2.667$ ($R^2 = 0.370$) [14] and $LL = 0.548*TK + 25.610$ ($R^2 = 0.276$) [13]. Further exploration revealed that different parts of LL could be mainly adjusted by different structures; in detail, the LLUA tends to be largely affected by TK ($B = 0.418$, $P < 0.001$), while the LLLA, geometrically equal to SS [4], should be more subject to regulation by the pelvis ($B = 0.576$, $P < 0.001$), presumably owing to the intrinsic anatomical adjacency [13]. Likewise, these novel findings are also supported by the Roussouly classification [4]. For example, despite the differences in TK between type 1 and type 2, the LLLA or SS seems to remain nearly unaffected in the two types (mean 30° and 32°, respectively) as determined by their approximately same PI values (mean 41° and 44°, respectively). Moreover, the LLUA is thought to remain relatively constant despite some distinctions between type 1 (average 22°) and type 2 (average 19°) [4], which might be attributable to the fact that the extent of TK is not further differentiated in types 3 and 4. In fact, the LLUA was indeed variable (mean 21.50° ± 5.02°, from 7° to 35°) among asymptomatic groups, which was also observed in our case series (mean 15.7° ± 6.0°, from 3.0° to 33.4°). Hence, it is irrational to implement a reconstructive operation for the lumbar spine solely by relying on PI, which may be one reason for mechanical complications [7,11], and TK, as another critical element, similarly plays an essential role in lumbar alignment, particularly on the LLUA [11,13].

Our findings in this study offer new insights into the regulatory mechanisms underlying sagittal alignment within the spinopelvic unit, which can enrich the Roussouly classification. On the other hand, such valuable algorithms responsible for patient-specific lumbar parameters appear to be extremely important tools for yielding a more accurate and individualized surgical strategy to regain a satisfactory sagittal alignment. Recovery of the desired sagittal alignment will greatly contribute to reducing postoperative mechanical complications and improving clinical consequences [6–8]. In addition, a thorough comprehension of these effective models can facilitate the recognition of pathological changes in sagittal alignment in symptomatic patients. According to these regression equations, surgeons can also evaluate the rationality of lumbar alignment created following surgical corrections and then estimate the potential risks of corrective failure (Figs. 6 and 7).

Despite the benefits mentioned above, some limitations must also be discussed. First, many other factors, including age, back muscles and abdominal pressure, can also influence lumbar alignment [15,23,24]; consequently, we need to systematically consider various relevant factors together for a more precise prediction of LL in future studies. Next, given the ethnic and regional differences in normal spinopelvic alignment [25], our results may be suitable for only the local population; to adequately address this issue, ongoing large-scale and multicentre datasets must be obtained from diverse cohorts of different races and areas. Moreover, despite the flexibility of the thoracic spine being finite,

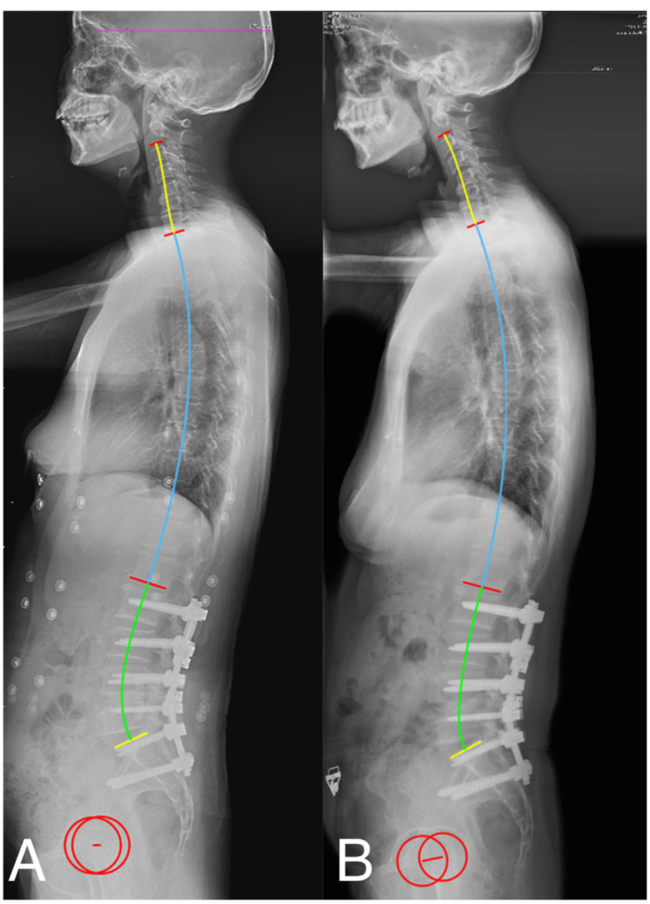

Fig. 6. 63-year-old female. A, immediate postoperative imaging, pelvic incidence = 43.0°, thoracic kyphosis = 34.6°; lumbar apex (L4), lumbar lordosis (42.7°), the upper arc (17.7°) and lower arc (25.0°) were approximately matched to the theoretical values (L4, 43.5°, 15.4° and 28.3°, respectively). B, no mechanical complications at 2-year follow-up.

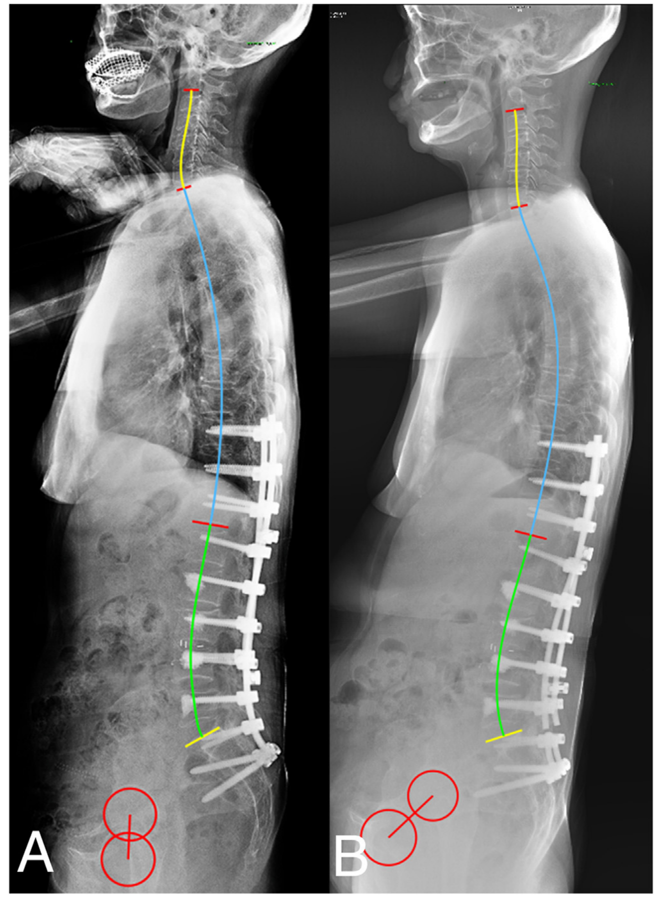

Fig. 7. 67-year-old female. A, immediate postoperative imaging, pelvic incidence = 65.7°, thoracic kyphosis = 23.6°; lumbar apex (L4), lumbar lordosis (39.2°), the upper arc (9.7°) and lower arc (29.5°) were not matched to the theoretical values (L3, 52.8°, 10.8° and 41.4°, respectively). B, bilateral rod breakage at 1-year follow-up.

TK is undeniably not completely constant, unlike PI, and may have a certain compensatory or pathological variance before surgery [26]; thus, researchers need to identify the physiological TK under the mobility of the thoracic spine to design a more appropriate lumbar shape in the future. Finally, the regulatory theory does not completely equal to the theories of spinal correction surgeries; due to space limitations, the formulae were not further analyzed by the results of operation. As surgeons currently treat by restoring the "normal" alignment recommended, a prospective long-term follow-up with a larger dataset should be performed to validate our conclusions.

5. Conclusion

In general, the specific lumbar geometry should be modulated by both pelvic and thoracic morphology. Such predictive models for sagittal lumbar parameters determined by individual PI and TK have been provided, and they allow surgeons to better comprehend the mechanisms regulating sagittal spinopelvic alignment and reconstruct an ideal lumbar alignment for patients.

Source of funding

The manuscript submitted does not contain information about medical device(s)/drug(s). No funds have been received for research.

Author contributions

Changyu Pan and Guodong Wang conceived the study design. Xiaobin Wang, Lei Kuang, Xiaoyang Liu and Tao li supervised the data collection and analysis. Changyu Pan drafted the manuscript. Bing Wang, Xingang Cui, Jianmin Sun and Guohua Lv contributed to the revision. Changyu Pan, Guohua Lv and Jianmin Sun are responsible for this article.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Acknowledgement

The authors thank the Department of Imaging in Shandong provincial hospital and The second Xiangya hospital, for providing the image data.

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