Realignment of Ideal Lumbar Lordosis in Correction Surgery: A Novel Predictive Formula

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Research Article

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Abstract

Study design: Retrospective cohort study

Summary of Background Data: Restoring the sagittal balance is the significant procedure, which could be evaluated by the relationship of thoracic kyphosis (TK) and lumbar lordosis (LL). Several lumbar lordosis predictive formulas have been proposed. But previous study ignored importance of reciprocal relationship between regional spinal modifications in some ways.

Objectives: Realignment of the lumbar lordosis is fundamental in spinal surgery and several formulas have been established to predict the appropriate lumbar lordosis. However, the predictive accuracy of these formulas did not reach their targets. The present study introduced a novel predictive formula for realignment of lumbar lordosis in correction surgery, aiming to predict the individualized ideal lumbar lordosis for different patients.

Methods: A total of 311 asymptomatic volunteers were recruited: 220 volunteers for the development of the formula, and the other 91 subjects for validation. General and radiological parameters were evaluated. Correlation analysis between maxLL and other parameters was performed. Multiple regression analysis was conducted to establish the predictive formula using variables related to maxLL. Comparison between predicated maxLL yielded by our formula and other 7 formulas and actual maxLL were conducted to determine the reliability and validity of our predictive formula.

Results: MaxLL was correlated with maxTK, SS, PT and PI (all P<0.05). The adjusted multiple regression analysis showed that there were significant associations of maxLL with maxTK and PI (all P<0.001), and the formula was established as follows: maxLL=0.6*maxTK+0.5*PI+3. No significant difference was found between actual maxLL and predicted maxLL yielded by our formula (P=0.408), and our predictive formula has been demonstrated sound reliability and validity.

Conclusion: MaxTK and PI were the primary contributors to maxLL, and our novel formula could be safely utilized to predict the ideal lumbar lordosis for patients before surgery.

Introduction

It has been widely believed that reasonable spinopelvic sagittal alignment plays a key role in the patient’s health-related quality of life (HRQOL), as many spinal and pelvic sagittal parameters have shown substantial correlations with the evaluation of physical function, pain, mental health, self-image and satisfaction with treatment\textsuperscript{1–7}. Therefore, restoring the sagittal balance is the fundamental procedure in various spine diseases correction surgeries\textsuperscript{7–10}. In addition, the whole spinal balance is characterized by the connected effects among spinopelvic elements. In particular, the reciprocal relationship between thoracic kyphosis (TK) and lumbar lordosis (LL) suggest their unique importance in the sagittal balance\textsuperscript{8,13}. Furthermore, loss of lumbar lordosis has been verified to be significantly associated with patients’ poor clinical outcome\textsuperscript{14–15}. Therefore, in order to achieve the optimal sagittal balance, it is
necessary to restore the normal reciprocal relationships between regional spinal modifications (TK and LL) in correction surgery, especially for the restoration of optimal lumbar lordosis\textsuperscript{8,16−18}. Nevertheless, the realignment of lumbar lordosis has remained one of the most challenging parts, which even more in severer sagittal imbalance patients\textsuperscript{11,12}. Osteoectomy is considered as a feasible treatment option to restore sagittal balance, such as Smith-Petersen osteoectomy (SPO), pedicle subtraction osteoectomy (PSO), vertebral column resection (VCR) and et al.\textsuperscript{19−21}. Although several lumbar lordosis predictive formulas have been proposed for the recovery of ideal lumbar lordosis\textsuperscript{17,22−25}, how to adjust the optimal sagittal balance is still full of confusion. The variables applied by these formulas were controversial, and the importance of reciprocal relationship between regional spinal modifications was ignored, which consequently affect the accuracy of prediction\textsuperscript{26,27}.

Therefore, we performed this retrospective study to introduce a novel predictive formula for ideal lumbar lordosis using more comprehensive spinopelvic parameters, and evaluate its reliability of prediction effect, which aims to improve the prediction accuracy and restore sagittal balance in spine surgery better.

**Material And Methods**

**Enlisted Population**

A total of 311 healthy volunteers from January 2017 to August 2018, who met the inclusion and exclusion criteria, were retrospectively reviewed. The inclusion criteria of study were as follows: a. healthy people without history of spinal disorders or spinal deformity; b. no history of spinal surgery. The exclusion criteria were: a. suspected diagnosis of lumbar spinal pathology and spinal deformities; b. tumors or infections; c. hip, knee, and ankle abnormalities. This study was approved by the Institutional Review Board in our university, and all subjects in our study provided written informed consent for the study.

**Data collection**

Demographic data of age were collected. Radiographic parameters were measured on lateral x-ray films of the whole spine by two individual surgeons, which including maximum thoracic kyphosis (maxTK, the Cobb angle measured between T4 and transitional vertebrae located at junction of thoracic kyphosis and lumbar lordosis)\textsuperscript{2,24}, maximum lumbar lordosis (maxLL, the Cobb angle measured between transitional vertebrae and S1)\textsuperscript{2,24}, sacral slope (SS, the angle between the horizontal and the sacral plate), pelvic tilt (PT, the angle between the vertical and the line through the midpoint of the sacral plate to femoral heads axis) and pelvic incidence (PI, angle subtended by a perpendicular from the upper endplate of S1 and a line connecting the center of the femoral head to the center of the upper endplate of S1). Compared with traditional measurement (TK: usually from T5-T12; LL: usually from L1-S1), maxTK and maxLL were evaluated and analyzed in our study, which could represent the real magnitude of thoracic and lumbar curve as the ranges of thoracic and lumbar curve varied among different individuals.

**Development and Validation of the Predictive Formula**
Patients were randomly assigned into two groups. A cohort of 220 volunteers was recruited in Group A for the development of our predictive formula, and the remaining 91 subjects were recruited in Group B for validation of this new formula. In the first analysis (development of predictive formula), correlation analysis between maxLL and other parameters including age, maxTK, PT, SS and PI was performed. Unadjusted multiple regression analysis was performed to find out the primary contributors to maxLL, and then adjusted multiple regression analysis, which used spinopelvic morphological parameters rather than postural parameters, was conducted to establish predictive formula for maxLL.

The second analysis was the validation of our newly developed formula. The predicted maxLL yielded by our's and other 7 formulas and actual maxLL were compared to detect whether there was significant difference, and test the reliability of newly developed formula. The other lumbar lordosis predictive formulas included: $\text{LL} = 0.508 \times \text{PI} - 0.088 \times \text{Age} + 28.6$ proposed by Xu et al. $^{17}$, $\text{LL} = 0.45 \times \text{PI} + 31.8$ proposed by Yamato et al. $^{28}$, $\text{LL} = 0.96 \times (0.74 \times \text{PI} + 0.8) + 17.42$ proposed by Lee et al. $^{25}$, $\text{LL} = 1.087 \times (0.548 \times \text{PI} + 12.7) + 21.61$ proposed by Legaye et al. $^{22}$, $\text{LL} = \text{PI} + 9$ proposed by Schwab et al. $^{23}$, $\text{maxLL} = -2.72 - 1.1 \times \text{PI} + 1.1 \times \text{PT} - 0.31 \times \text{maxTK}$ proposed by Vialle et al. $^{24}$ and $\text{LL} = 45 - \text{TK} - \text{PI}$ proposed by Rose et al. $^{29}$.

**Statistical analysis**

Statistical analyses were performed using SPSS 17.0 statistics software (SPSS Inc., Chicago, IL). Descriptive statistics were listed in the form of mean and standard deviation. Independent two-sample t-test was used to compare the differences of variables between Group A and Group B. maxLL and its correlation with other parameters were analyzed by correlation coefficient test. Multiple regression analysis was conducted to find out the independent association between potential factors and maxLL. The predicted maxLL yield by formulas and actual maxLL were compared using the paired t-test. $P < 0.05$ was selected as significant level.

**Results**

A total of 220 asymptomatic volunteers were recruited in Group A for the development of predictive formula with the mean age of 46 years old. The 91 healthy subjects were recruited in Group B for the validation of newly developed formula with the mean age of 46.68 years old. There were no significant differences of variables between Group A and Group B, as shown in Table 1.

Correlation coefficient test indicated that correlation was observed between maxLL and maxTK ($r = 0.564$, $P < 0.001$), SS ($r = 0.783$, $P < 0.001$), PT ($r = -0.155$, $P = 0.021$) and PI ($r = 0.483$, $P < 0.001$). However, no correlations were found between maxLL and age ($r = -0.031$, $P = 0.643$). All the data were summarized in Table 2. Unadjusted multiple linear regression analysis was conducted by using variables that were found to be significantly correlated with maxLL, and the results suggested that maxTK ($P < 0.001$) and SS ($P < 0.001$) were the primary contributors to maxLL, while the influence of PT and PI on lumbar curves were not so strong ($P = 0.477$ and $0.629$, respectively). However, the parameters of SS and PT changes with the posture of spine and pelvis, so the prediction abilities were poor. So we adjusted the regression analysis, removing SS and adding morphological parameter of PI, the result showed that maxTK and PI were...
significantly associated with maxLL, and finally we developed a novel ideal lumbar lordosis predictive formula: \( \text{maxLL} = 0.6 \times \text{maxTK} + 0.5 \times \text{PI} + 3 \), as shown in Table 3.

In the analysis of validation of predictive formula, there was no significant difference between actual maxLL and predicted maxLL yielded by our formula \( (P = 0.408) \), and significant correlation was also found between actual maxLL and predicted maxLL \((r = 0.683, P < 0.001, \text{Fig. 1})\). Although no significant difference was also observed between the actual maxLL and predicted LL yielded by Xu et al.’s \((P = 0.799)\) and Vialle et al.’s formula \((P = 0.085)\), these findings might not be accurate enough. On the one hand, Xu et al.’s formula\(^{17}\) was established on the measurement of LL, rather than maxLL, which might be smaller than the actual lumbar lordosis. On the other hand, Vialle used unstable morphological parameter PT to develop the formula, and the prediction results might be unstable as well. In addition, there were significant differences between actual maxLL and predicted maxLL yielded by Yamato et al.’s, Lee et al.’s, Legaye et al.’s, Schwab et al.’s, and Rose et al.’s formula \((P < 0.001)\), suggesting great gap between actual maxLL and predicted maxLL yielded by these formulas. All the data were shown in Table 4 and a typical case was presented in Fig. 2.

**Discussion**

Restoring the sagittal alignment in the correction surgery has gotten increasing recognition of importance among spine surgeons\(^{1–7}\). However, it is a hard task to fully grasp every sagittal parameter, because some morphological parameters such as PI remains constant before and after surgery, and the other parameters change greatly and are difficult to predict\(^{30}\). Lumbar lordosis is one of sagittal parameter that is feasible to restore directly in the correction surgery\(^{8,28,29}\). Furthermore, in order to achieve the optimal spinopelvic sagittal balance, it is necessary to reconstruct ideal lumbar lordosis\(^{17,18}\), and accurately predict the magnitude of postoperative lumbar lordosis with high sensitivity before surgery\(^{26}\).

However, although several predictive formulas\(^{17,22–25,28,29}\) have been established to determine the target value of lumbar lordosis, variables recruited in these formulas were various and the actual prediction effectiveness remained controversial. Only PI was recruited in predictive formula and LL could be determined using ‘LL = 0.45*PI + 31.8’ in Yamato et al.’s study\(^ {28}\). In Rose et al.’s formula\(^ {29}\), the LL might be predicted by the formula \( \text{LL} \leq 45o-\text{TK-PI} \). These formulas either used one-sided parameters or parameters change with spinopelvic position, so they cannot accurately predict the ideal lumbar lordosis. So we performed this retrospective study and introduce a novel predictive formula using more comprehensive spinopelvic parameters, and then evaluated its reliability of prediction.

In our study, maxLL was significantly associated with maxTK \((r = 0.564, P < 0.001)\), SS \((r = 0.783, P < 0.001)\), PI \((r = 0.483, P < 0.001)\) and PT \((r = -0.155, P = 0.021)\), which suggested that the larger maxTK, PI and SS of the population is, the larger their maxLL will be, and vice versa, the smaller PT, the larger maxLL. The compensatory mechanisms of keeping sagittal balance are so complicated that it is a result of a reaction between the ground and an ideal dynamic chain between the spine, pelvis and lower limbs\(^ {31}\).
The spine of patients suffering from lumbar degenerative diseases and low back pain is characterized by the loss of LL and SS, anterior sagittal imbalance and increase of PT, and several compensatory mechanisms occurred to keep the whole sagittal balance, including reduction of maxTK and pelvic retroversion (increase of PT and decrease of SS), which could be verified in our findings. However, although no association was found between maxLL and age (r=-0.031, P = 0.643), we also found negative relationship between age and maxLL, which was consistent with Xu et al.’s study (r=-0.37).

In the unadjusted regression analysis, variables significantly associated with maxLL were included and analyzed and the results showed that maxTK and SS were the primary contributors to the maxLL. The sagittal spinal balance has been described as reciprocal curves of TK and LL, and the relationship between TK and LL play a key role in the sagittal balance. In addition, the extension of adjacent segments (changes of TK and LL) is also an important compensatory mechanism of keeping sagittal balance. Therefore, it could be easily understood why maxTK has significant impact on the morphology of lumbar lordosis. SS was a positional parameter changing with age and pelvic position and also a compensatory mechanism of keeping sagittal balance, hence it was an importance contributor in the prediction of LL as well. However, the parameters of SS changes with the position of spine and pelvic, which is not stable enough to predict lumbar lordosis, in addition, the compensatory reaction often did not occur because of the lack of motion in the spino-pelvic junction in the postoperative unphysiological spine, making us difficult to predict the compensatory parameters (SS and PT) before the surgery. Furthermore, how to restore the positional parameters like SS and PT accurately in correction surgery remains a challenge for surgeons. Therefore, it is not reasonable to use SS to predict ideal maxLL.

PI is a fixed morphological parameter, which remains constant with the increasing age and changes of position. Compared with other pelvic parameters, PI plays a more dominant role in the shape of sagittal curves. Therefore, many researchers used PI to estimate ideal LL based on this theory. Furthermore, significant correlation was observed between PI and SS in our study (r = 0.680, P < 0.001), which was consistent with Vialle et al.’s study (r = 0.81) and Mac-Thiong et al.’s study (r = 0.76). Considering the factor that it is difficult to predict SS before the surgery, that PI plays a dominant role in the shape of lumbar lordosis and that PI is significantly correlated to SS, we replaced PI for SS in our adjusted regression analysis (all P < 0.001), and established a novel ideal lumbar lordosis prediction formula as follows: maxLL = 0.6*maxTK + 0.5*PI + 3.

In the analysis of validation, the mean value of predicted maxLL using our formula was 49.32°, and there was no significant difference between actual maxLL and our predicted maxLL (P = 0.408), suggesting a potent power of prediction. When comparing actual maxLL with predicted maxLL yielded by Yamato et al., Lee et al., Legaye et al., Schwab et al. and Rose et al., we found significant difference between actual maxLL and predicted maxLL yielded by these authors. In Yamato et al.’s, Lee et al.’s, Legaye et al.’s and Schwab et al.’s study, only PI was used to predict the ideal maxLL in their formulas. In our opinion, it is not appropriate if we only use PI to predict the ideal LL as lumbar lordosis.
has been verified to be affected by many variables\textsuperscript{17}, which should not be neglected. Although TK was used as a parameter in Rose et al.’s formula\textsuperscript{29} along with PI, significant difference was also observed between actual maxLL and predicted maxLL yielded by their formula. In their study\textsuperscript{29}, the predicted formula was proposed by their hypotheses rather than scientific methods, although they found that the inclusion of both TK and PI displayed the greatest sensitivity in predicting LL, which might be primary contributor to their formula’s low effectiveness of prediction. In Xu et al.’s study\textsuperscript{17} age was included in their predictive formula, and there was no significant difference observed between actual maxLL and predicted maxLL yielded by their formula. However, we believed that the prediction effectiveness of Xu et al.’s formula could be contributed to the correlation between age and maxTK ($r = 0.283, P < 0.001$), PT ($r = 0.266, P < 0.001$) and SS ($r = -0.213, P = 0.001$), rather than age itself, because age was not found to be significantly associated with maxLL in our correlation test and unadjusted regression analysis. This could be contributed to the different measure methods to assess lumbar lordosis (LL and maxLL) between our and Xu et al.’s study and measure errors between different surgeons as well. In addition, no significant difference was also found between actual maxLL and predicted maxLL yielded by Vialle et al.’s study\textsuperscript{24}, nevertheless, the prediction stability of formula was limited due to influence of spine and pelvic position and surgery choice on PT measurement, and too many variables affect the convenience of the formula application.

Furthermore, other two important things should be noticed when using our predictive formula. Firstly, all the values of parameters used in our formula were pre-operative values. PI remains constant before and after surgery, however, we should notice that the mean value of maxTK used in our formula is also pre-operative value because maxTK in majority of patients with mild or moderate sagittal balance remains constant if we do not perform osteoectomy at thoracic vertebras. With regard to patients with severe sagittal imbalance, osteoectomy is usually needed to perform at lower thoracic segments even at upper thoracic segments, therefore, the impact of osteoectomy on maxTK should be considered when we use this formula. Secondly, the lumbar lordosis restored during the spinal surgery might be smaller than our predicted maxLL as spontaneous compensation of pelvic parameters should be considered.

Although a robust and reliable formula was proposed in our study, there are some limitations of this study that should be addressed. First, all the patients we recruited in our study came from a single-center study and might result in the selection bias and compromise the statistical power. Second, sagittal parameters have been verified to be different between males and females; therefore, the predicted formula might be different between males and females, which was not evaluated in our study. Therefore, large-scaled and multicenter studies should be performed to make a more comprehensive research.

**Conclusion**

MaxTK and PI were the primary contributors to maxLL, and our novel formula was established as follow: $\text{maxLL} = 0.6*\text{maxTK} + 0.5*\text{PI} + 3$, which could be safely utilized to predict the ideal lumbar lordosis for patients before surgery.
Abbreviations

HRQOL: health-related quality of life;
TK: thoracic kyphosis;
LL: lumbar lordosis;
SPO: Smith-Petersen osteotomy;
PSO: pedicle subtraction osteotomy;
VCR: vertebral column resection;
maxTK: maximum thoracic kyphosis;
maxLL: maximum lumbar lordosis;
SS: sacral slope;
PT: pelvic tilt;
PI: pelvic incidence.

Declarations

Ethics approval and consent to participate

This study was approved by the ethics committee of our university (Local Ethics Committee of Changhai Hospital, SMMU, No. CHEC20170163). And all subjects in our study provided written informed consent for the study.

Consent for publication

As authors, we are willing to publish this article and hope that research colleagues can discuss the research problems in this field and make further progress.

Availability of data and materials

The data that support the findings of this study are available from Changhai Hospital, China but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Changhai Hospital, China.

Competing interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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**Authors' contributions**

Kai Chen, Yilin Yang, Heng Wang and Tianjunke Zhou contributed equally to this paper. And Xiao Zhai, Changwei Yang as well as Ming Li did the contribution in modification and instruction.

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**References**


Tables

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<td>Group A</td>
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<td>Group B</td>
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<td>maxTK</td>
<td>Group A</td>
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<td>maxLL</td>
<td>Group A</td>
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<td>SS</td>
<td>Group A</td>
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<td>PT</td>
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<td>Age</td>
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<td>Age</td>
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<td>maxTK</td>
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<td><strong>Unadjusted</strong></td>
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<td>PI</td>
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**Table 4** Comparison of actual maxLL and predicted maxLL/LL in different equations

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<th>Author</th>
<th>Equations</th>
<th>Recruited subjects</th>
<th>Actual maxLL (mean ± SD)</th>
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<tr>
<td>Our formula</td>
<td>maxLL=0.6<em>maxTK+0.5</em>PI+3</td>
<td>Asymptomatic volunteers</td>
<td>48.70 ± 9.46</td>
<td>maxLL: 49.32 ± 7.69</td>
<td>-0.62 ± 7.06</td>
<td>0.408</td>
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<td>Xu et al.17</td>
<td>LL=0.508<em>PI-0.088</em>Age+28.6</td>
<td>Asymptomatic volunteers</td>
<td>48.70 ± 9.46</td>
<td>LL: 48.93 ± 5.68</td>
<td>-0.23 ± 8.55</td>
<td>0.799</td>
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<tr>
<td>Yamato et al.28</td>
<td>LL=0.45*PI+31.8</td>
<td>ASD patients</td>
<td>48.70 ± 9.46</td>
<td>LL: 53.51 ± 4.80</td>
<td>-4.80 ± 8.40</td>
<td>P&lt;0.001</td>
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<td>Lee at al.25</td>
<td>LL=0.96*(0.74*PI+0.8)+17.42</td>
<td>Asymptomatic volunteers</td>
<td>48.70 ± 9.46</td>
<td>LL: 52.37 ± 7.59</td>
<td>-3.66 ± 8.97</td>
<td>P&lt;0.001</td>
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<td>Legaye et al.22</td>
<td>LL=1.087*(0.548*PI+12.7)+21.61</td>
<td>Young adults</td>
<td>48.70 ± 9.46</td>
<td>LL: 64.28 ± 6.41</td>
<td>-15.57 ± 8.62</td>
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<td>Schwab et al.23</td>
<td>LL=PI+9</td>
<td>One asymptomatic adult</td>
<td>48.70 ± 9.46</td>
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<td>-8.41 ± 10.48</td>
<td>P&lt;0.001</td>
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<td>Vialle et al.24</td>
<td>maxLL=-2.72-1.1<em>PI+1.1</em>PT-0.31*maxTK</td>
<td>Asymptomatic volunteers</td>
<td>48.70 ± 9.46</td>
<td>maxLL: 49.60 ± 8.88</td>
<td>-0.89 ± 4.90</td>
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<td>Rose et al.29</td>
<td>LL=45-TK-PI</td>
<td>Patients underwent PSO</td>
<td>48.70 ± 9.46</td>
<td>LL: 40.15 ± 14.15</td>
<td>8.55 ± 10.34</td>
<td>P&lt;0.001</td>
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Figures
Figure 1

The scatterplot of predicted maxLL and measured maxLL values ($r=0.683$, $P<0.001$).
A female volunteers, 26 years old. maxTK was measured from T3 to T12 with mean value of 38.37º; (actual) maxLL was measured from T12 to S1 with mean value of 48.76º; PI was measured with mean value of 43.18º. According to our predictive formula (maxLL=0.6*maxTK+0.5*PI+3), predicted maxLL=0.6*38.37º+ 0.5*43.18º+3=47.612º, nearly equals to actual maxLL.