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ORIGINAL ARTICLE

Age estimation based on pelvic ossification using regression models from conventional radiography

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Abstract To establish regression models for age estimation from the combination of the ossification of iliac crest and ischial tuberosity. One thousand three hundred and seventy-nine conventional pelvic radiographs at the West China Hospital of Sichuan University between January 2010 and June 2012 were evaluated retrospectively. The receiver operating characteristic analysis was performed to measure the value of estimation of 18 years of age with the classification scheme for the iliac crest and ischial tuberosity. Regression analysis was performed, and formulas for calculating approximate chronological age according to the combination developmental status of the ossification for the iliac crest and ischial tuberosity were developed. The areas under the receiver operating characteristic (ROC) curves were above 0.9 ($p < 0.001$), indicating a good prediction of the grading systems, and the cubic regression model was found to have the highest R-square value ($R^2 = 0.744$ for female and $R^2 = 0.753$ for male). The present classification scheme for apophyseal iliac crest ossification and the ischial tuberosity may be used for age estimation. And the present established cubic regression model according to the combination developmental status of the ossification for the iliac crest and ischial tuberosity can be used for age estimation.

Keywords Ossification · Iliac crest · Ischial tuberosity · Age estimation · Regression analysis

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Introduction

Age estimation in living individuals is an area of increasing importance for both radiology and forensic medicine. Though the developmental status of a child can be assessed from various parameters such as height, weight, secondary sexual characteristics, and dental age, the skeletal age assessment has been considered the most reliable method [1]. Currently, the most commonly applied methods used worldwide are the Greulich and Pyle (GP) and Tanner and Whitehouse (TW2, TW3), both based on radiographs of the left hand and the wrist. The GP method is used by means of comparing the radiographies of the evaluated case with the radiography samples in the template series [2]. The TW method is based on obtaining a score for the relevant bones through a detailed structural analysis and the sum of points assigned to the bones based on this analysis [3]. At present, age estimation were obtained from the skeleton development of hand [4, 5], medial epiphysis of the clavicle [6–9], cervical vertebra [10], temporal bone [11], mandibular ramus [12], teeth development [13–15] and so on; the development of the medial epiphysis of the clavicle plays a major role for the important legal age threshold of 18 years [6–9].

The secondary pelvic ossification centers (iliac crest, anteroinferior iliac spine, ischial spine, and ischial tuberosity), as well as ossification centers in the triradiate cartilage, sacroiliac joint, and symphysis pubis, generally ossify just before and during puberty and adolescence. Apart from the clavicle and the skeletal elements of the hand, the apophysis of the iliac crest [16–18] and the ischial tuberosity [19–21] provide good possibilities for determining skeletal age due to a relatively late completion of maturation. In 2011, a sonographic pilot study demonstrated the iliac crest apophysis (ICA) to be principally suitable for forensic age estimation in the living [22]. In 2013, two more studies investigated different classification

systems applied to pelvic radiographs in order to further establish the ICA as a possible criterion for forensic age estimation [17], and ICA/the iliac wing (IW) ratios were calculated and used for regression analyses, yielding different regression equations for age estimation [18].

Our previous study repeated a classification scheme for apophyseal iliac crest ossification [23] in Chinese by referring to the previous classification systems [17] and differentiating four stages of ossification for the iliac crest, and repeated the classification system for the ischial tuberosity developmental status of the ossification [24] in Chinese by referring to the previous classification systems [25, 26] and differentiating seven stages of ossification for the ischial tuberosity. In the present study, we aimed to establish regression models for age estimation from the combination of the ossification of iliac crest and ischial tuberosity.

Table 1 Frequency distribution by biological sex and age cohort

Age (year)	Male	Female	Total
14.00–14.99	49	38	87
15.00–15.99	70	35	105
16.00–16.99	76	56	132
17.00–17.99	71	47	118
18.00–18.99	81	45	126
19.00–19.99	90	51	141
20.00–20.99	53	58	111
21.00–21.99	56	52	108
22.00–22.99	62	55	117
23.00–23.99	61	55	116
24.00–24.99	54	56	110
25.00–25.99	52	56	108
Total	775	604	1379

Materials and methods

One thousand three hundred and seventy-nine conventional pelvic radiographs at the West China Hospital of Sichuan University between January 2010 and June 2012 were collected from routine medical investigations and evaluated retrospectively, and both ossification status of iliac crest and ischial tuberosity can be evaluated from each radiograph. All participants are from the West China Han group, the ones taking drugs and/or suffering diseases affecting their skeletal development were excluded intentionally from our research. The population with reliable examination included 604 female (43.8 %) and 775 male (56.2 %) individuals. The subjects were aged between 14 and 26 years. Table 1 shows sample sizes by sex and age group for the 1379 cases in which reliable assessment of the ossification status was possible. The present study was performed with the approval of the ethics committee of the West China Hospital of Sichuan University, and all the participants provided written informed consent.

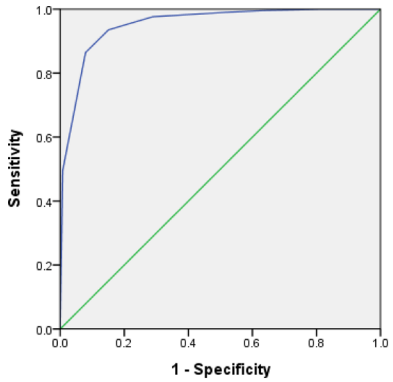
The pelvic radiographs were done according to standard procedures: lying patient, anterior/posterior path of rays, approx. 81 kV on average, and usage of a digital luminescence radiography system. Image evaluation was done on screen using a workstation at syngo fast view.

The developmental status of the ossification for the iliac crest and ischial tuberosity were evaluated referring to previous studies [17, 18, 22–26]. The classification scheme differentiate four stages of ossification for the iliac crest; stage 2 and stage 3 were divided into three sub-classification stages. Stage 1 was scored as 1. Stage 2 and stage 3 were scored as 2 to 4 and 5 to 7, respectively, according to the developmental status. Stage 4 was scored as 8. Likewise, the ossification status for the ischial tuberosity of stage 0 to stage 6 was scored as 1 to 7, respectively. The sum of both scores in the individual pelvic radiograph was defined as X. Regression analysis was conducted with age as dependent variable and X as independent variable to establish a mathematical model for age estimation. Eleven regression models were used which were linear, logarithmic, inverse, quadratic, cubic, compound, power, S-curve, growth, exponential and logistic. Each regression model will produce R-square value and its parameters. R-square value represents the correlation between age and X, and the parameters will produce an equation for age estimation. The regression model with the highest R-square value for each gender was chosen as the best correlation with age. The receiver operating characteristic (ROC) analysis was performed to measure the value of estimation of 18 years of age for Chinese with the present classification scheme for the iliac crest and ischial tuberosity. Statistical analyses were performed using SPSS (VERSION 19.0 for Windows). A level of significance of 0.05 ($p<0.05$) was adopted for all the tests. Intra-class correlation coefficients were determined in order to evaluate intra-observer agreement.

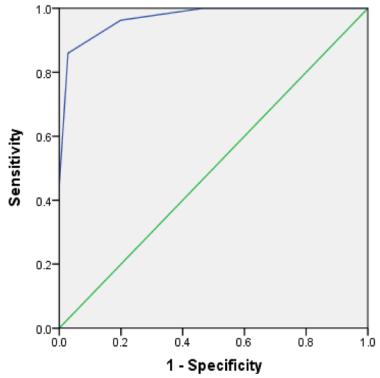
Results

No statistical significant differences were found between the right and left pelvic sides ($p>0.05$). Hence, in the following paragraphs, only the left pelvic side is regarded. Calculation of intra-class correlation coefficients revealed very good intra-observer agreements ($R=0.916$ for iliac crest and $R=0.906$ for ischial tuberosity). Figure 1 shows the ROC curve for estimating the age of 18 years derived from the ossification of iliac crest and ischial tuberosity. The areas under the ROC curves were above 0.9 ($p<0.001$), indicating a good prediction of the grading systems.

Regression analysis was performed to establish a fitted mathematical model. All the results were summarized in Table 2. Figure 2 shows the correlation between the X and

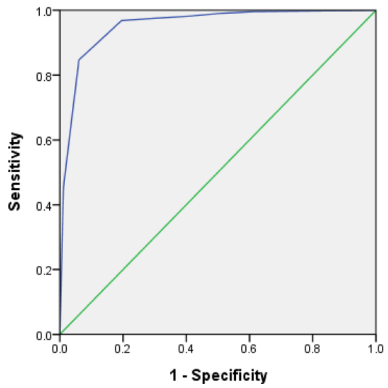


AUC = 0.953, 95% CI 0.938 - 0.968, p ＜ 0.001 for male

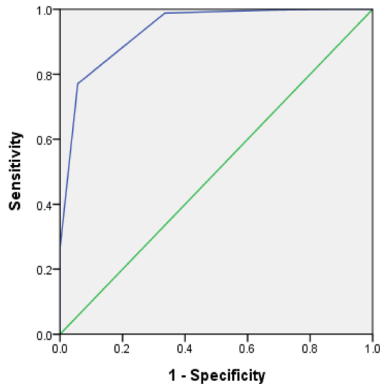


AUC = 0.970, 95% CI 0.958 - 0.982, p ＜ 0.001 for female

The ossification of iliac crest



AUC = 0.954, 95% CI 0.938 - 0.969, p ＜ 0.001 for male



AUC = 0.936, 95% CI 0.916 - 0.957, p ＜ 0.001 for female

The ossification of ischial tuberosity

Fig. 1 ROC curve for estimating the age 18 years from the ossification of iliac crest and ischial tuberosity

age of the collected subject for both gender. The bold line indicated in the figure (cubic regression) is the best fit line describing that particular correlation. The cubic regression model was found to have the highest R-square value ($R^2 = 0.744$ for female and $R^2 = 0.753$ for male). The equation from the cubic regression analysis for female was:

$$\text{Age} = 18.196 - 1.637X^3 + 0.204X^2 - 0.005X.$$

The equation from the cubic regression analysis for female was:

$$\text{Age} = 14.408 + 0.475X^3 - 0.064X^2 + 0.005X.$$

Table 2 Mathematic regression models for age estimation from the ossification of iliac crest and ischial tuberosity

Models	Female			Male		
	R^2	*F* value	*P* value	R^2	*F* value	*P* value
Linear regression	0.693	1357	0.000	0.673	1590	0.000
Logarithmic regression	0.565	782.27	0.000	0.545	926.57	0.000
Inverse regression	0.342	312.68	0.000	0.385	483.12	0.000
Quadratic regression	0.742	863.43	0.000	0.748	1145	0.000
Cubic regression	0.744	582.40	0.000	0.753	782.52	0.000
Compound regression	0.724	1581	0.000	0.713	1921	0.000
Power regression	0.603	914.97	0.000	0.591	1116	0.000
S-curve regression	0.375	360.91	0.000	0.426	574.33	0.000
Growth regression	0.724	1581	0.000	0.713	1921	0.000
Exponential regression	0.724	1581	0.000	0.713	1921	0.000
Logistic regression	0.724	1581	0.000	0.713	1921	0.000

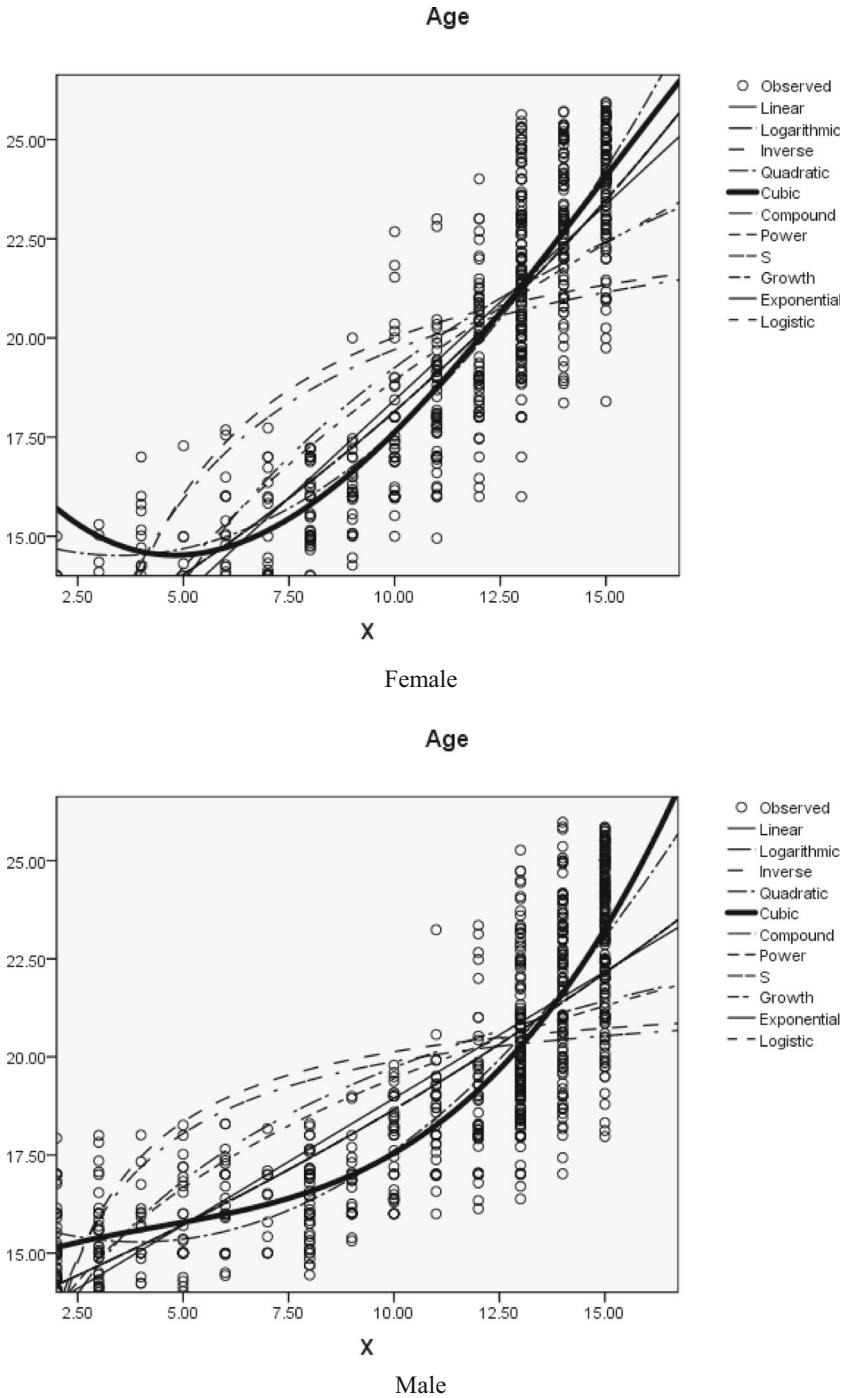


Fig. 2 Correlation between *X* and age for all regression models. The *circle* signs are the age of the collected subjects. The *lines* are the correlation between the ossification and age of subjects for 11 regression models

Discussion

The hand and wrist conveniently possess many bones and epiphyses that mature in a well-defined progression over time and which are also easily evaluated on single radiographs [2]. Similarly, the ossification for the iliac crest and ischial tuberosity can be easily collected from single pelvic radiographs. Although, radiation-free methods such as magnetic resonance imaging and ultrasonography can be used for examinations of the pelvis, the ultrasound examination is difficult for assessment in the case of existing adiposity [27], and subclassification did not appear feasible due to the limitations of MRI [28].

Correct age estimation of the accused is important during criminal proceedings. The age of relevance to criminal liability changes according to the national interest. In most countries, age thresholds range between 14 and 18 years. In China, the age thresholds of relevance for criminal proceedings are

14, 16, and 18 years, reaching the age of 18 years, the most significant step for the legal assessment of numerous aspects of criminal, civil and asylum law. In order to offer a valuable alternative method for assessing 18 years of age, the clavicle is recommended due to its slowest and most prolonged development [29]. The apophysis of the iliac crest [16–18] and the ischial tuberosity [19–21] are suitable for forensic age diagnostics due to a comparatively late completion of osseous maturation. The present study repeated a classification scheme for apophyseal iliac crest ossification [23] in Chinese by referring to the previous classification systems [17] and differentiating four stages of ossification for the iliac crest, and repeated the classification system for the ischial tuberosity developmental status of the ossification [24] in Chinese by referring to the previous classification systems [25, 26]. Receiver operating characteristic (ROC) analysis was performed to measure the value of estimation of 18 years of age with the present classification scheme for the iliac crest and ischial tuberosity; the areas under the ROC curves were above 0.9 ($p < 0.001$), indicating a good prediction of the grading systems.

Recently, the regression models were obtained from the skeleton development to estimate age. Regression analysis is a popular choice due to its simplicity and comparative accuracy compared to the other two methods (the GP method and TW method). The regression model itself consists of various types and some of those that have been used for age estimation are linear regression [12, 14, 30], multiple regression [13, 31], single quadratic regression [32], S-curve regression [4, 15], and support vector regression [32]. The coefficient of determination (R^2) was 0.564 for the pulp chamber volume of first molars [15], 0.49 for the tooth-coronal index of permanent mandibular first molar [14], 0.81 for the length of the mandible ramus [12], 0.775 in female, and 0.815 in male for the knee [30]. For the pelvic ossification, a pilot study established a regression model, which describes age as a linear function of percentage, yielded a linear regression equations for the ICA/IW ratio; however, the ICA/IW ratio showed only moderate correlations with the subjects' chronological age because all the calculated coefficients of determination (R^2) were <0.4 ($R^2 = 0.38$ for male and $R^2 = 0.20$ for female) [18]. In the present study, regression analysis was performed and formulas for calculating approximate chronological age according to the combination developmental status of the ossification for the iliac crest and ischial tuberosity were developed. Finally, the cubic regression model was found to have the highest R-square value ($R^2 = 0.744$ for female and $R^2 = 0.753$ for male).

However, there were limitations in the present study. Our data was collected from routine medical investigations, but the methods of our results must be applied with caution because of the radiation to the gonadal organs from standard pelvic radiography.

To conclude, our research indicated that the present classification scheme for apophyseal iliac crest ossification and the ischial tuberosity may be used for age estimation. And the present established cubic regression model according to the combination developmental status of the ossification for the iliac crest and ischial tuberosity can be used for age estimation.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflicts of interest.

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