Thumb Ossification Composite Index (TOCI) for Predicting Peripubertal Skeletal Maturity and Peak Height Velocity in Idiopathic Scoliosis

A Validation Study of Premenarchal Girls with Adolescent Idiopathic Scoliosis Followed Longitudinally Until Skeletal Maturity

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Background: Accurate skeletal maturity assessment is important to guide clinical evaluation of idiopathic scoliosis, but commonly used methods are inadequate or too complex for rapid clinical use. The objective of the study was to propose a new simplified staging method, called the *thumb ossification composite index* (TOCI), based on the ossification pattern of the 2 thumb epiphyses and the adductor sesamoid bone; to determine its accuracy in predicting skeletal maturation when compared with the Sanders simplified skeletal maturity system (SSMS); and to validate its interrater and intrarater reliability.

Methods: Hand radiographs of 125 girls, acquired when they were newly diagnosed with idiopathic scoliosis prior to menarche and during longitudinal follow-up until skeletal maturity (a minimum of 4 years), were scored with the TOCI and SSMS. These scores were compared with digital skeletal age (DSA) and radius, ulna, and small hand bones (RUS) scores; anthropometric data; peak height velocity; and growth-remaining profiles. Correlations were analyzed with the chi-square test, Spearman and Cramer V correlation methods, and receiver operating characteristic curve analysis. Reliability analysis using the intraclass correlation (ICC) was conducted.

Results: Six hundred and forty-five hand radiographs (average, 5 of each girl) were scored. The TOCI staging system was highly correlated with the DSA and RUS scores ($r = 0.93$ and 0.92, $p < 0.01$). The mean peak height velocity (and standard deviation) was 7.43 ± 1.45 cm/yr and occurred at a mean age of 11.9 ± 0.86 years, with 70.1% and 51.4% of the subjects attaining their peak height velocity at TOCI stage 5 and SSMS stage 3, respectively. The 2 systems predicted peak height velocity with comparable accuracy, with a strong Cramer V association (0.526 and 0.466, respectively; $p < 0.01$) and similar sensitivity and specificity on receiver operating characteristic curve analysis. The mean age at menarche was 12.57 ± 1.12 years, with menarche occurring over several stages in both the TOCI and the SSMS. The growth remaining predicted by TOCI stage 8 matched well with that predicted by SSMS stage 7, with a mean of <2 cm/yr of growth potential over a mean of <1.7 years at these stages. The TOCI also demonstrated excellent reliability, with an overall ICC of >0.97.

Conclusions: The new proposed TOCI could provide a simplified staging system for the assessment of skeletal maturity of subjects with idiopathic scoliosis. The index needs to be subjected to further multicenter validation in different ethnic groups.

Accurate skeletal maturity assessment is important for prediction of curve progression and clinical management of idiopathic scoliosis, including bracing decisions and counseling about prognosis. Determination of the timing of peak height velocity and growth remaining is of paramount importance for these purposes[1-5]. However,

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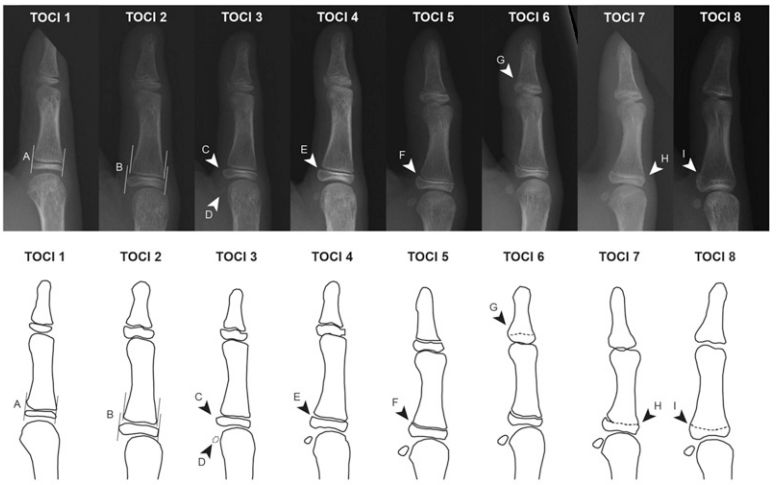
commonly used clinical or radiographic methods are inadequate or too complex for rapid application in a busy clinic setting[6,7].

Sanders et al.[6] demonstrated that the Tanner-Whitehouse-3 (TW3)[8] radius, ulna, and small bones of the hand (RUS) scores had the highest correlation with the curve acceleration phase among all skeletal maturity parameters in idiopathic scoliosis. The scoring system is, however, time-consuming and requires the use of an atlas with a substantial learning curve[3,4,6,7]. Sanders et al. simplified the RUS score into a digital skeletal age (DSA) score, by excluding the scoring of the distal aspect of the radius and the ulnar epiphysis, and confirmed that the DSA score had excellent correlation with the curve acceleration phase as well[6].

An ideal skeletal maturity assessment system would be simple and reliable with good predictability of peak height velocity and correlation with the standard DSA scoring system. We attempted to further simplify the current skeletal maturity staging system by focusing on the morphology of a minimum number of essential hand ossification centers that we hoped would reliably predict the skeletal maturity information from the whole hand in a quicker and easier manner. Previous studies[8,9] had revealed that the epiphyses of the distal and proximal phalanges of the thumb demonstrated radiographic changes that were similar to those of the epiphyses of the ulnar 4 digits during the pubertal period. The adductor sesamoid has also been



Components Of TOCI	TOCI 1 Stage	TOCI 2 Stage	TOCI 3 Stage	TOCI 4 Stage	TOCI 5 Stage	TOCI 6 Stage	TOCI 7 Stage	TOCI 8 Stage
Adductor sesamoid bone	unossified	unossified	*ossified	ossified	ossified	ossified	ossified	ossfied
Distal phalangeal epiphysis of thumb[$]	open	open	open	open	open	*fused	fused	fused
Ulnar corner of proximal phalangeal epiphysis of thumb[%]	*covered	*covered	covered	*capped (early)	*capped (advanced)	capped (advanced)	*partial fusion	*fused

[$] "Fused" epiphysis is defined as completed absence of black band of physis, any residual physis that remained unfused is referred to as "open".
[%] Refer to Figure 7 for method to distinguish early capping from advanced capping.
* **Key radiological features (A-I) of maturity indicators in different TOCI stages.**

TOCI 1	A: Width of thumb proximal phalangeal epiphysis same as that of the metaphysis.
TOCI 2	B: Width of thumb proximal phalangeal epiphysis exceeds that of the metaphysis (covered epiphysis).
TOCI 3	C: Roundish covered (without capping) ulnar corner of thumb proximal phalangeal epiphysis. D: Appearance of the ossified adductor sesamoid bone.
TOCI 4	E: Early capping of ulnar corner of thumb proximal phalangeal epiphysis.
TOCI 5	F: Advanced capping of ulnar corner of thumb proximal phalangeal epiphysis.
TOCI 6	G: Thumb distal phalangeal epiphysis completely fused.
TOCI 7	H: Thumb proximal phalangeal epiphysis partially fused (both black & white band).
TOCI 8	I: Thumb proximal phalangeal epiphysis completely fused.

Fig. 1

TOCI stages 1 through 8 and the corresponding ossification pattern and sequence of the adductor sesamoid, distal phalangeal epiphysis, and proximal phalangeal epiphysis.

extensively used to predict pubertal onset for decision-making regarding maxillofacial surgery[9-12]. After conducting a validation study and confirming the very high concordance rate (71.3%) between TW staging of the thumb epiphyses and that of the ulnar 4 digital epiphyses[13], we developed a new thumb classification based on the epiphyses of the distal and proximal phalanges together with the adductor sesamoid bone, which we call the "thumb ossification composite index (TOCI)" (Fig. 1). We hypothesized that this new simpler staging system could reliably predict when skeletal maturity would be reached by a subject in the early peripubertal period.

The objective of this study was to compare the TOCI with a current simplified system for prediction of skeletal maturity and validate its interrater and intrarater reliability.

Materials and Methods

Hand radiographs were prospectively collected from a longitudinal cohort of girls with clinically and radiographically confirmed idiopathic scoliosis recruited from a scoliosis clinic in a tertiary hospital. The inclusion criteria were (1) female sex, (2) premenarche, (3) an age of 8 to 12 years at the time of entry into the study, (4) a diagnosis of idiopathic scoliosis, (5) no clinical evidence of neurological abnormality, (6) no abnormalities of skeletal maturation, (7) a Risser sign of zero with open physes in the hand, and (8) completion of at least 6 follow-up visits over a minimum of 4 years. Demographic variables that were collected included the ages when the radiographs were made, standing height, sitting height, body weight, and arm span. Institutional review board approval was obtained (ethics approval reference number 2016.045).

All patients were followed at an average of 6-month intervals starting prior to menarche, with more frequent visits during the early peripubertal growth period to capture accurately the timing of peak height velocity, until skeletal maturity was confirmed by the radiographic appearance of physeal closure of the distal radial epiphysis. In accordance with the original TW3 protocol, posteroanterior radiographs of the left hand were obtained at each

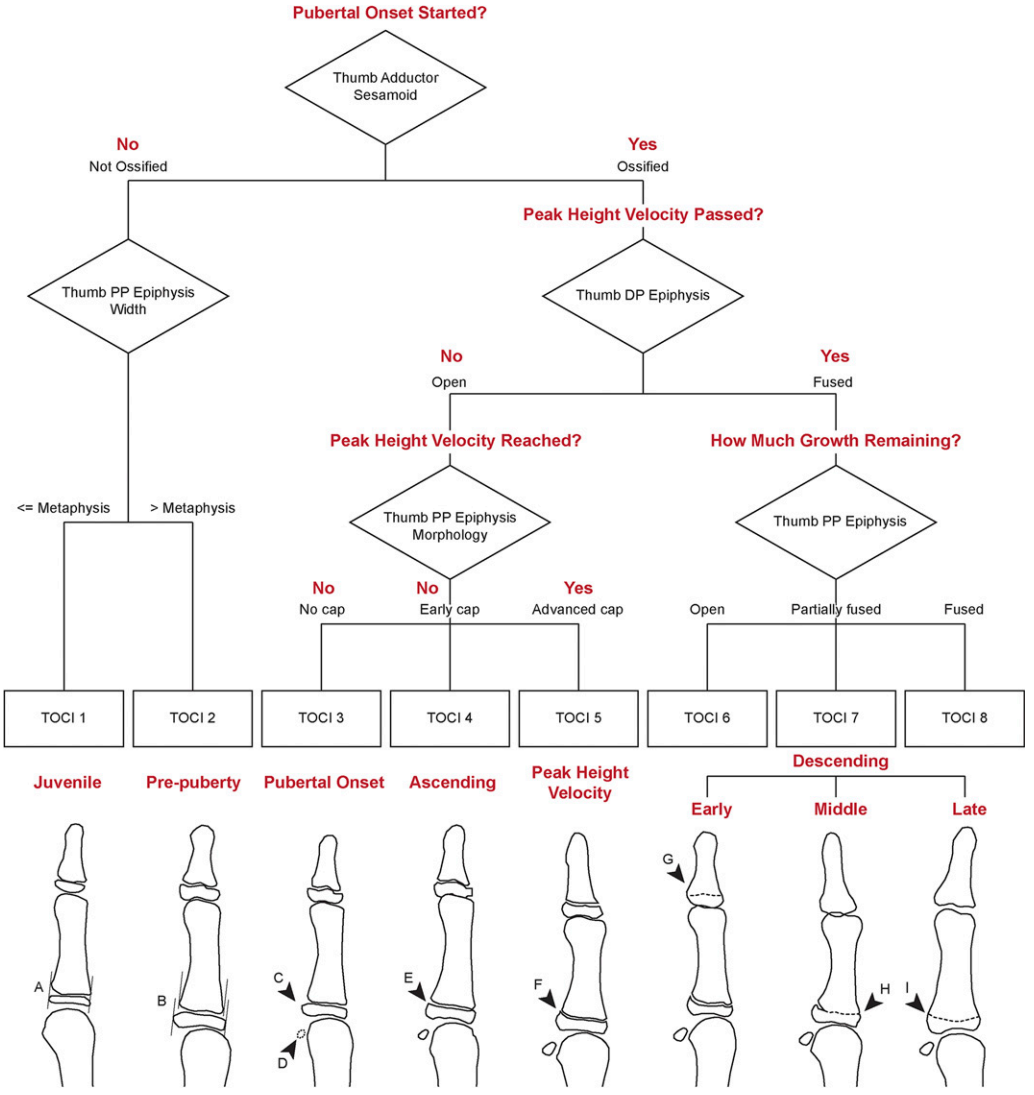


Fig. 2

Algorithm for TOCI staging. The words in red refer to the clinical decision-making algorithm. PP = proximal phalangeal and DP = distal phalangeal. Also see the short training video on TOCI staging included with this article.

visit[8]. All hand and wrist radiographs were independently reviewed by the principal author and another experienced orthopaedic clinical fellow to establish the stage of skeletal maturity according to (1) the proposed TOCI method algorithm based on the 2 thumb epiphyses and the adductor sesamoid (Fig. 2) and (2) the standard TW method based on the epiphyses of the small bones (distal phalanx, middle phalanx, proximal phalanx, and metacarpal) of the first, third, and fifth digits as well as the radial and ulnar epiphyses. Both investigators were blinded to the chronological age and identity of the patients. The TW stages (E through I) and TOCI stages (1 through 8) were recorded on separate data sheets, which were then collected by a third independent coinvestigator for subsequent analysis. TW-derived RUS and DSA scores were calculated. The Sanders simplified skeletal maturity scoring system (SSMS)[4] was included for comparison to determine the accuracy of TOCI staging in predicting the timing of peak height velocity and menarche. Peak height velocity was calculated using the minimum 6-month interval method[8,14,15]. To define the accuracy in predicting the final growth remaining, the magnitude, time interval, and velocity of the growth occurring after the final TOCI stage (8) were compared with those parameters following a similar SSMS stage (7). All TOCI and SSMS scores were tabulated against the chronological age when the score was obtained and at menarche as well as peak height velocity.

Reliability Test

The principal investigator scored all radiographs using the TOCI method, and another investigator, who was not involved in the study, grouped the radiographs by stage across the whole TOCI spectrum (stages 1 through 8). Nine radiographs were then selected randomly from each TOCI stage, to ensure an equal distribution of test radiographs demonstrating each stage, resulting in 63 radiographs for testing (none were stage 1). One clinical fellow, 2 orthopaedic residents, and 3 non-medical assistants were invited to serve as novices for reliability testing.

An interactive training session (see the instructional video on TOCI staging included with this article [Video 1]) was provided to all 6 reviewers to give the details of the TOCI. For the reliability testing, the reviewers were instructed to view the radiographs on a high-resolution computer monitor and were allowed to refer to the reference materials (Fig. 2). All reviewers were blinded to the chronological age of the patients and performed the ratings independently with no time limit. After 4 weeks, all reviewers repeated the ratings using the same set of radiographs.

Statistical Analysis

Descriptive statistics and Spearman correlation coefficients were calculated for the DSA and RUS scores in comparison with the TOCI staging system. Charts were created to determine the timing of menarche and peak height velocity at different maturity stages in the TOCI and SSMS systems. The chi-square test and Cramer V correlation were used to evaluate the accuracy of the 2 systems in predicting the peak height velocity. The area under the receiver operating characteristic curve was also used to determine the cutoff stages in the 2 systems with the best sensitivity and specificity (highest percentages) to predict peak height velocity. Reliability analysis was tested with Cronbach alpha values. Intraclass correlations (ICCs) in different kinds of comparisons were carried out. The statistical analyses were done with SPSS version-20.0 software (IBM). The significance level was $p < 0.05$.

Results

In a 5-year period (2007 through 2011), 645 hand and wrist radiographs were collected consecutively from 125 premenarchal girls with adolescent idiopathic scoliosis followed longitudinally until skeletal maturity, so that the patients had an average of 5 follow-up radiographs each. The mean ages (and standard deviations [SDs]) when the first and last radiographs available for analysis were made were 10.9 ± 0.8 and 13.7 ± 1.0 years, respectively. The last radiograph was defined as the earliest radiograph that demonstrated TOCI stage 8. None of the patients in our cohort had TOCI stage 1.

Correlation of TOCI Staging with SSMS System

The TOCI stages were found to correlate strongly with both the DSA ($r = 0.93$, $p < 0.01$) and the RUS ($r = 0.92$, $p < 0.01$) score.

TABLE I Correlation of TOCI and SSMS Stages with Chronological Age and DSA and RUS Scores

	Age *(yr)*			DSA Scores			RUS Scores		
	Mean (SD)	Median	Range	Mean (SD)	Median	Range	Mean (SD)	Median	Range
TOCI stage									
2	10.9 (0.8)	10.7	10.2-12.6	306.2 (49.7)	332.0	221.0-363.0	455.3 (70.7)	469.0	332.0-573.0
3	11.4 (0.7)	11.1	10.6-13.3	344.7 (34.5)	353.5	293.0-397.0	549.6 (76.9)	556.0	441.0-683.0
4	11.7 (0.8)	11.6	10.1-13.8	385.4 (27.9)	390.5	293.0-429.0	640.9 (50.0)	641.0	481.0-748.0
5	12.2 (0.9)	12.1	10.1-15.0	417.0 (30.9)	415.0	351.0-542.0	716.6 (52.8)	706.0	608.0-857.0
6	12.8 (0.9)	12.8	10.5-15.5	505.3 (42.5)	508.0	392.0-571.0	840.9 (69.8)	836.5	562.0-962.0
7	13.2 (0.9)	13.2	11.1-16.0	570.4 (21.7)	571.0	513.0-609.0	938.5 (44.0)	947.0	786.0-1,000.0
8	13.7 (1.0)	13.8	11.6-16.4	602.6 (12.5)	609.0	540.0-609.0	988.9 (21.5)	1,000.0	909.0-1,000.0
SSMS stage									
1	11.0 (0.9)	10.5	10.2-12.6	300.9 (61.9)	341.0	221.0-363.0	466.5 (74.2)	465.5	380.0-573.0
2	11.7 (0.8)	11.6	10.2-13.8	376.4 (36.2)	374.0	293.0-450.0	625.8 (83.6)	641.0	332.0-761.0
3	12.3 (1.0)	12.3	10.1-15.5	413.3 (23.2)	415.0	351.0-514.0	715.3 (52.6)	705.5	613.0-905.0
4	12.6 (1.0)	12.6	10.9-16.0	472.5 (42.2)	466.0	401.0-562.0	790.7 (67.3)	791.0	668.0-953.0
5	13.0 (0.8)	12.9	11.0-15.0	524.5 (29.0)	527.0	466.0-568.0	865.0 (76.1)	876.5	556.0-954.0
6	13.2 (1.0)	13.3	10.5-15.9	568.6 (31.6)	567.0	453.0-609.0	934.0 (60.0)	948.0	731.0-1,000.0
7	13.5 (0.9)	13.5	11.6-14.9	600.7 (19.1)	609.0	502.0-609.0	987.8 (31.5)	1,000.0	784.0-1,000.0

The correlations of the TOCI and SSMS stages with chronological age and the DSA and RUS scores are shown in Table I and summarized in the integrated growth chart in Figure 3.

Comparison of TOCI and SSMS Staging of Key Growth Parameters

Timing of Peak Height Velocity

One hundred and seven patients with clearly identifiable growth peaks were used for this analysis. The mean peak height velocity was 7.43 ± 1.45 cm/yr (range, 5 to 11.95 cm/yr) and occurred at mean age of 11.93 ± 0.86 years (range, 9.73 to 13.99 years).

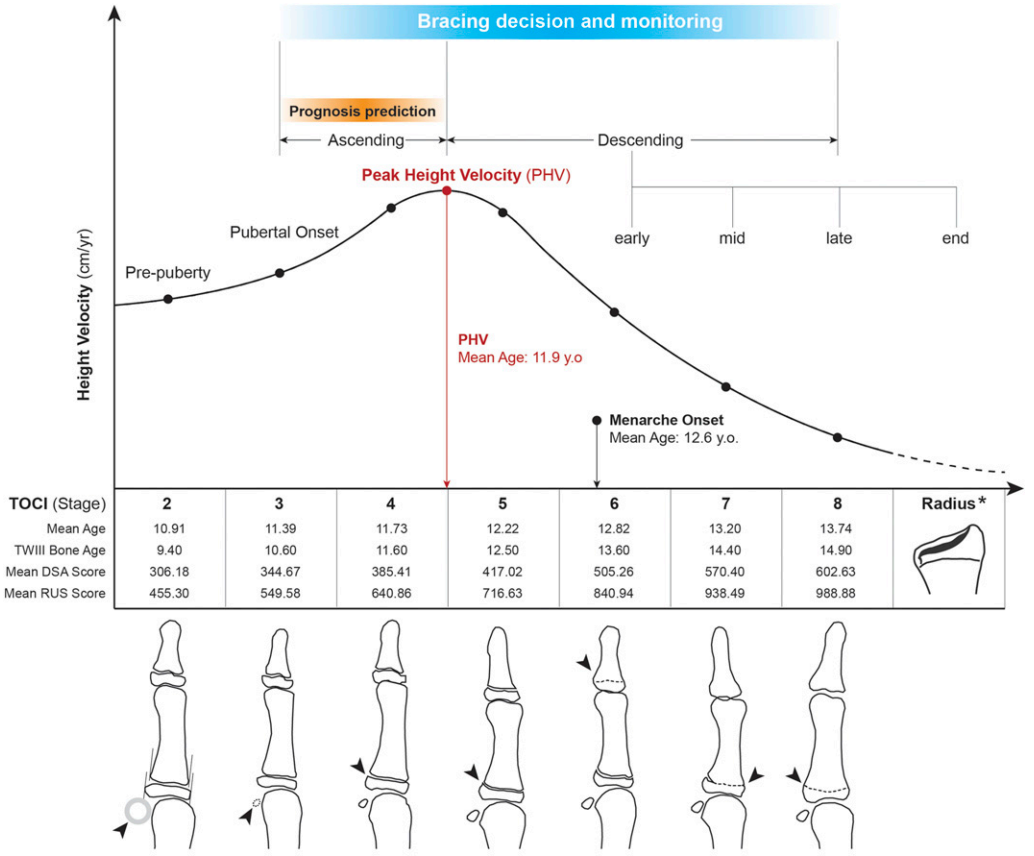
Both the TOCI and the SSMS stages were strongly associated with the peak height velocity as confirmed by strong Cramer V correlations (0.526 and 0.466, respectively), with statistical significance ($p < 0.01$).

As shown in Figure 4, 70.1% and 51.4% of the subjects attained their peak height velocity at TOCI stage 5 ± 0.60 and SSMS stage 3 ± 0.99, respectively, both with a median DSA score of 415.

The analysis of the area under the receiver operating characteristic curve indicated that the cutoff stages that predicted the timing of peak height velocity with the best sensitivity and specificity were TOCI stage 4.5, with a sensitivity of 93.6% and a specificity of 72.2%, and SSMS stage 2.5, with a sensitivity of 90.8% and a specificity of 75.0%.

Timing of Menarche

The mean age at menarche was 12.57 ± 1.12 years (range, 9.4 to 14.3 years), and menarche was found to occur over several stages in both the TOCI and the SSMS (Fig. 5).

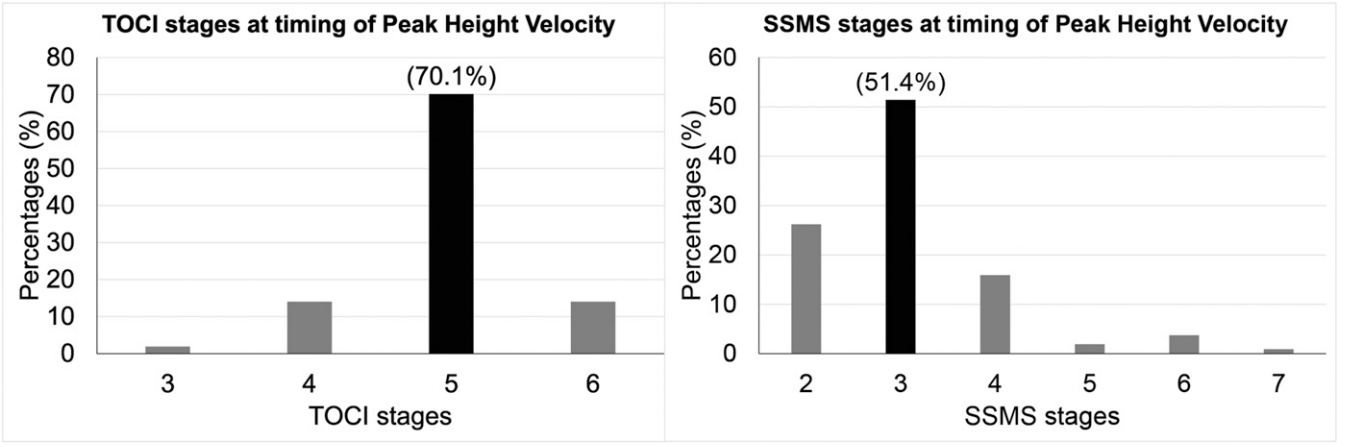


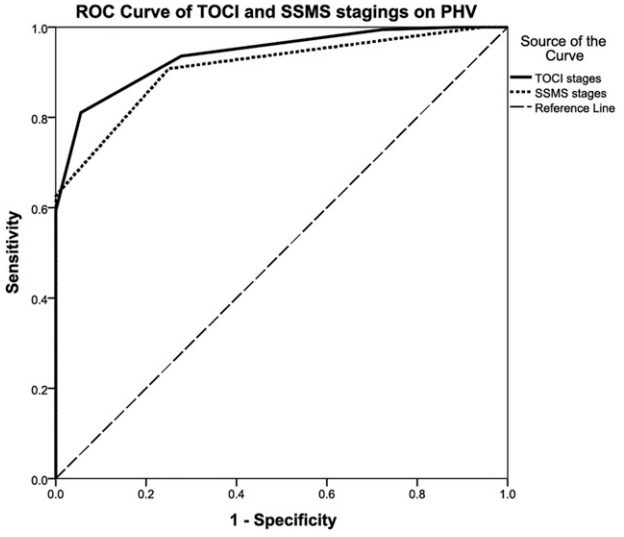
Key maturity indicators represented in TOCI stages which signify different phases of pubertal growth

TOCI 1/2: Absence of adductor sesamoid indicates *pre-puberty period*.
TOCI 3: First appearance of ossified adductor sesamoid signifies *pubertal onset*.
TOCI 4: Ulnar corner of thumb PP epiphysis starting to cap indicates *the ascending phase of growth close to PHV*.
TOCI 5: Advanced capping along ulnar corner of PP epiphysis coincident with *critical PHV period*.
TOCI 6: DP physis complete fusion marks the start of *descending phase of growth* when menarche commonly starts.
TOCI 7: Partial fusion of PP epiphysis indicates further slowing of growth rate.
TOCI 8: Completed fusion of PP epiphysis confirms *late maturity*.
* Radial fusion marks the *end of skeletal growth*.

Fig. 3

Integrated pubertal growth chart showing the crucial phases in the peripubertal growth period until skeletal maturity matched with the corresponding TOCI stages, mean DSA and RUS scores, and chronological and bone ages. PHV = peak height velocity, PP = proximal phalangeal, and DP = distal phalangeal.





Area Under the Curve

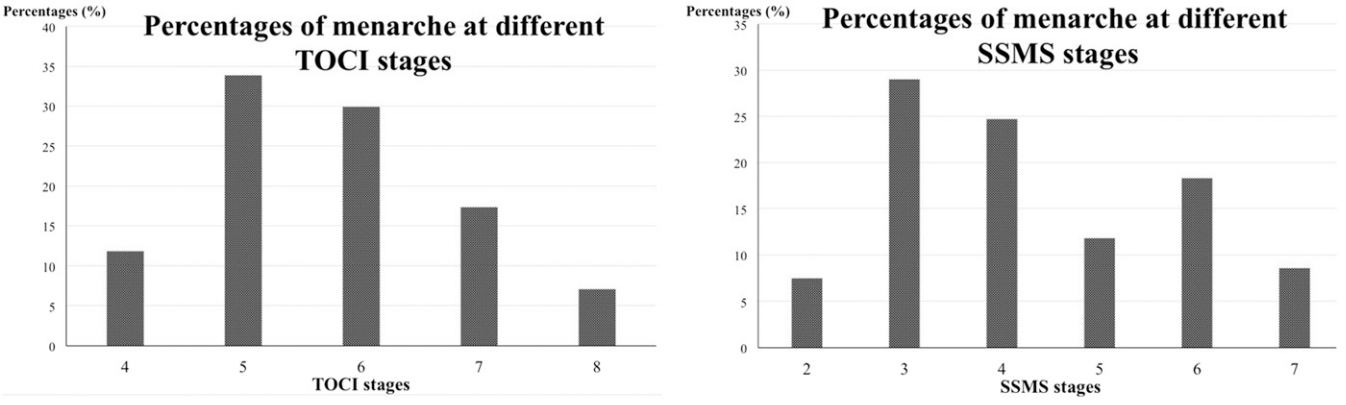
Test Result Variable(s)	Area	Std. Error	Asymptotic Sig.	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
TOCI stages	.939	.015	.000	.910	.969
SSMS stages	.910	.019	.000	.873	.947

	Cutoff stages	Sensitivity (%)	Specificity (%)
TOCI stages	4.5	93.6	72.2
SSMS stages	2.5	90.8	75.0

n=107	TOCI stages	SSMS stage
Mean	4.96	3.08
SD	0.60	0.99

Fig. 4

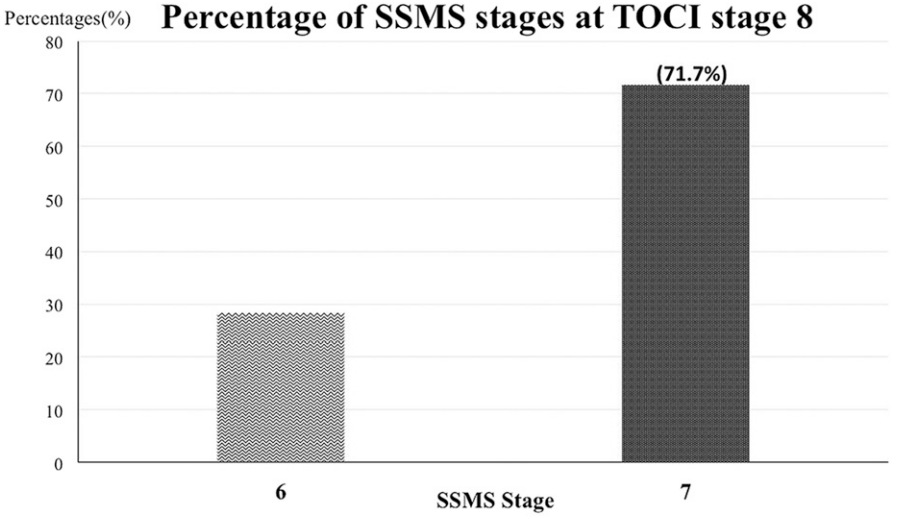
Comparison of descriptive statistics, percentage distributions, and results of receiver operating characteristic (ROC) curve analysis of the TOCI and SSMS to determine the timing of peak height velocity (PHV).



n=125	TOCI	SSMS
Mean stages	5.83	4.3
SD	0.98	1.46

Fig. 5

Percentage distribution of menarche occurring at different TOCI and SSMS stages.



	TOCI 8	SSMS 7
Mean absolute remaining growth (cm)	2.50±1.27	2.68±1.45
Mean remaining growth period (years)	1.65±0.68	1.67±0.74
Mean height velocity (cm /year)	1.73±1.10	1.86±1.24

Fig. 6

The percentage of patients at SSMS stage 7 who were at TOCI stage 8 and the growth-remaining profiles at SSMS stage 7 and TOCI stage 8.

TABLE II Interrater and Intrarater Reliability Test Results for Orthopaedic Surgeons and Non-Medical Assistants*

	Junior Orthopaedic Surgeons	Non-Medical Assistants
Interrater		
First phase	0.976 (0.961-0.986)	0.985 (0.975-0.992)
Second phase, 4 wk later	0.990 (0.984-0.994)	0.988 (0.980-0.994)
Intrarater, first phase versus second phase	0.995 (0.992-0.997)	0.989 (0.981-0.994)

*The values are given as the reliability with the 95% confidence interval in parentheses.

Growth-Remaining Profile

We found that 71.7% of the subjects at TOCI stage 8 were at SSMS stage 7. The median DSA score at both stages was 609. Overall, the mean amount of final growth remaining at these 2 stages was <2 cm/yr over <1.7 years. The growth-remaining profiles are summarized in Figure 6.

Reliability Test

All 6 clinical professionals showed excellent interrater and intrarater agreement for the TOCI classification (Table II).

Discussion

An ideal bone maturity assessment model should be both simple and reliable for clinical usage, with good correlation to a standard scoring system. The excellent reliability of the TOCI demonstrated that it is easy to learn, with a relatively short learning curve even among novice users. More importantly, it also has excellent correlation with DSA and RUS scores.

Sanders et al. proposed an important simplified skeletal maturity scoring system[4] (SSMS) with 8 stages based on the ossification patterns of all digital epiphyses of the hand and using the same descriptors as utilized in the TW3 system. They reported that the SSMS had excellent correlation with the curve acceleration phase (r = 0.9) in 22 female subjects and excellent reliability among senior orthopaedic surgeons[4]. However, a subsequent validation study of 275 patients demonstrated a steep learning curve for less experienced users[16]. Other recently reported simplified models using the olecranon apophysis[17] or the distal part of the radius and the ulnar epiphysis[3] (DRU classification) were either not evaluated in strictly conducted longitudinal studies or not fully validated through comparison with the standard DSA and RUS scoring systems. The modified Risser grading system had low specificity and interobserver reliability[18].

As is the case for the existing systems[3,4,9,17], any proposed simplified system must be able to accurately predict the

timing of peak height velocity and menarche as well as the growth-remaining period to inform the clinical decision regarding bracing and prognostic counseling about curve progression.

The mean age at peak height velocity (11.93 ± 0.86 years) in our study was comparable with that in most previous studies[3,6,14,17,19]. The growth velocity magnitude was similar to that in Asian studies[3,19] and less than that in European[17] and U.S. studies[6,14]. The age at peak height velocity in our study of subjects with idiopathic scoliosis was delayed (by a mean of 1.47 years) compared with that of normal subjects[20,21], signifying a longer period of peripubertal growth, which may have an effect on curve progression. Radiographically, the preponderance of capping of the epiphyses of the distal and middle phalanges (of the ulnar 4 digits) and of the proximal phalanges and metacarpal bones (of all 5 digits) at SSMS stage 3 was found to best represent the timing of peak height velocity[4,5]. This stage corresponds well to stage 5 in our TOCI classification. The median DSA score at TOCI stage 5 was 415 (Table I), which coincides exactly with the reported critical DSA range of 400 to 425 (SSMS stage 3) that best matched with the timing of the peak height velocity and onset of the curve acceleration phase[6]. Our results showed that TOCI stage 5 had good accuracy for predicting peak height velocity compared with SSMS stage 3, as demonstrated by a better Cramer V association (0.526 versus 0.466), a narrower standard deviation (0.60 compared with 0.99), and similar sensitivity and specificity on receiver operating characteristic curve analysis (Fig. 4). More importantly, it is simpler to use TOCI stage 5 for this purpose as one only needs to pay attention to advanced capping over the ulnar corner of the proximal phalangeal epiphysis in the thumb.

The mean age at menarche onset in our study was 12.6 years, which was 8 months later than the mean age at peak height velocity (11.9 years), and menarche consistently occurred between the median ages at TOCI stages 5 and 6, representing the early descending phase of the growth curve. The wide range of menarche age in this series (9.4 to 14.3 years) indicated its limitation in accurately predicting remaining growth. This finding echoed the observations by Charles et al.[17] and Little et al.[14] and was similar to that in a study of 2,196 Chinese girls with adolescent idiopathic scoliosis[22]. As the onset of menarche is affected by multiple factors of growth, and because of the age spread and considerable overlapping with the timing of peak height velocity, menarche could not be matched with a single representative stage in either the SSMS or TOCI system (Fig. 5). In our series, 33.9% of the subjects had the onset of menarche at the TOCI stage at which peak height velocity occurred (TOCI stage 5), 54.3% had it after that stage (menarche began at stage 6, 7, or 8), and 11.8% had it before that stage (menarche began at stage 4). This pattern is similar to that reported in longitudinal studies by Little et al.[14], Tanner[8], and Buckler[15].

The growth-remaining prediction refers to the more advanced TOCI stages (6, 7, and 8), matched with the descending phase of pubertal growth (Fig. 3). TOCI stage 8 (completed fusion of the proximal phalangeal epiphysis of the thumb) is equivalent to SSMS stage 7 (completed fusion of all digital epiphyses) as evidenced by 71.7% concordance between these 2 systems and their comparable final growth-remaining profiles (Fig. 6). Radiographically, both the TOCI and the SSMS still rely on distal radial epiphyseal fusion status to determine the end of growth, although it is controversial whether clinically relevant growth is still possible at the late radiographic stages of fusion of the distal radial physis[16]. The SSMS may provide more clarity about growth remaining at this stage since it shows the distal radial physis.

The concept of using only the thumb distal phalanx, proximal phalanx, and adductor sesamoid to predict skeletal maturity is novel but derived from precedent. The distal and proximal phalangeal epiphyses of the thumb have been used in traditional methods for determining orthopaedic bone age (e.g., the Greulich and Pyle atlas[23] and the TW3 method[8]). The adductor sesamoid is known to be always present in adolescents[24], is easily detectable, and has been extensively used to estimate skeletal maturity in orthodontic surgery (by determining the onset of puberty, it is possible to predict facial growth and the timing for mandibular reconstruction[10-12]). In addition, the pronated position of the thumb proximal phalanx relative to the orientation of the 4 ulnar digits provides easier visualization of the capping of the epiphysis at a very early stage. The relatively large black "cartilage gap" allows further separation into early and advanced capping stages through the

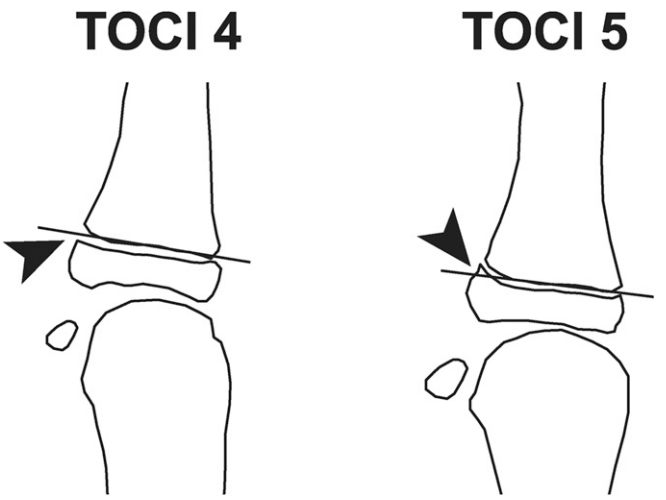


Fig. 7

Illustration of "early capping" of the proximal phalangeal epiphysis at TOCI stage 4 compared with "advanced capping" at TOCI stage 5. A reference line is drawn along the most distal osseous subchondral border of the proximal phalangeal metaphysis. "Early capping" is defined when the "capping" at the ulnar corner is below this reference line (left arrowhead), and "advanced capping" is defined when it touches or extends distal to this reference line (right arrowhead).

use of a reference line (Fig. 7). The thumb adductor sesamoid allows extra precision in predicting the onset of puberty[9-12]. The composite index score of the 2 thumb epiphyses and the adductor sesamoid corresponds well to different stages of pubertal growth curve as summarized in the integrated growth chart in Figure 3. Most importantly, because the thumb epiphyses and the adductor sesamoid are located so close to each other, they can be easily imaged with a magnified view through the use of a very low-radiation mini-mobile x-ray machine in the clinic.

To our knowledge, this is the first study to investigate the use of the thumb epiphyses to predict skeletal maturity in subjects with idiopathic scoliosis and to validate the method with a large number of longitudinal hand radiographs made before menarche and at an average of 6-month intervals in the peripubertal period. We believe that the newly proposed thumb ossification composite index (TOCI) was shown to be simple to use and to have excellent reliability and accuracy in the prediction of skeletal maturity comparable with the Sanders SSMS. It has the potential for application in a busy clinic setting. Further validation in larger multicenter studies involving different ethnic groups, males, longitudinal correlation with normal adolescents at different time points, and curve progression profiles are ongoing. ■

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