7 Standardization of skeletal maturity assessment

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Introduction

At the initial presentation of patients diagnosed with adolescent idiopathic scoliosis (AIS), appropriate management of these patients is based upon the consideration of multiple parameters. These parameters include the type and magnitude of the scoliotic curve, gender, age of onset, and most importantly, maturity status. By assessing the amount of growth potential remaining, clinicians can determine the risk of curve progression[1–4] and decide whether any treatment is needed promptly and make the prognosis of the treatment.[5]

Various maturity indicators have been used worldwide, including chronological age, menarchal status for girls, secondary sexual characteristics, and skeletal bone age. Both clinical and radiographic parameters can be used to assess growth status (**Table 7.1**). Skeletal maturity has been shown to be a reliable indicator for pubertal growth and for biological maturation.[6] However, the practice of using skeletal maturity measures varies between countries.[7] Since the growth pattern during pubertal growth spurt for each individual remains largely consistent,[8,9] a standardized approach for using skeletal maturity indices in growth assessment can be beneficial for the clinical management of AIS.

In this chapter, we aim to provide an overview of the various maturity assessment methods and provide recommendations on how to utilize them effectively in our daily clinical practice.

Table 7.1 Common skeletal and clinical parameters for assessing growth status

Clinical parameters	Radiological parameters
Chronological age	Risser staging (with/without modification using triradiate cartilage ossification)
Onset for menarche (for girls)	Tanner-Whitehouse staging
Secondary sexual characteristics	Greulich and Pyle atlas
• Tanner staging	DRU classification
➢ Pubic hair	Sanders skeletal maturity staging system
➢ Breast development	TOCI
➢ Testes, penis	Simplified olecranon method
Bodily growth	Cervical vertebral maturation method
• Body height	PHOS
➢ Standing	PFMI
➢ Sitting	
• Arm span	
• Foot length/shoe sizes	

Abbreviations: DRU, distal radius and ulna; PFMI, proximal femur maturity index; PHOS, proximal humerus ossification system; TOCI, thumb ossification composite index.

Importance of understanding skeletal growth in the management of AIS

Pubertal growth spurt is a critical period for patients with AIS. It begins with accelerated longitudinal growth of limbs, followed by the longitudinal growth in the axial skeleton. The onset and exacerbation of idiopathic scoliosis between the age of 10 and 18 years[10] make AIS distinctive, as the amount of rapid significant growth during adolescent growth spurt[11] can be accompanied by marked deterioration of the spinal curvature. This is in comparison to early onset scoliosis whose management will be different, involving prepubertal growth and with the emphasis on preserving the development of the spine, thoracic cage, and pulmonary function.[12,13]

For AIS, different treatment options include appropriate monitoring, bracing, and surgical correction of the curve. Management of AIS needs identification of the timing of pubertal growth landmarks: the acceleration phase, peak growth with peak height velocity (PHV), growth deceleration, and growth cessation.[9,14] The *timing* of these pubertal events is the key factor determining treatment outcomes, such as the success of brace treatment, or whether any postoperative relapse like the crankshaft phenomenon[15] occurs in patients receiving early surgery. By assessing the degree of epiphyseal growth plate ossification and fusion, the process of bone maturation can be used to estimate the potential for further linear growth.[16] The maturity status indicates the proper timing of initiating and completing the treatment, aiming to optimize treatment outcomes and to preserve the outcomes achieved.[17,18]

The relationship between the risk of scoliotic curve progression and the remaining growth potential should be emphasized.[9] Significant relationships were demonstrated between skeletal maturation stages, growth rate, and curve progression rate in AIS.[19–23] Pubertal growth spurt begins approximately at 9 to 10 years for girls and 11 to 12 years for boys whose growth spurt is of a longer duration.[11] At the time with rapid adolescent skeletal growth, main curve progression occurred.[3,24] Curve changes can be an increase of 1° to 2° per month (amounting to 12° per year) at the beginning of the growth acceleration phase.[14,25] Therefore, close monitoring of the curve is warranted to identify its acceleration phase prior to PHV (**Fig. 7.1**).

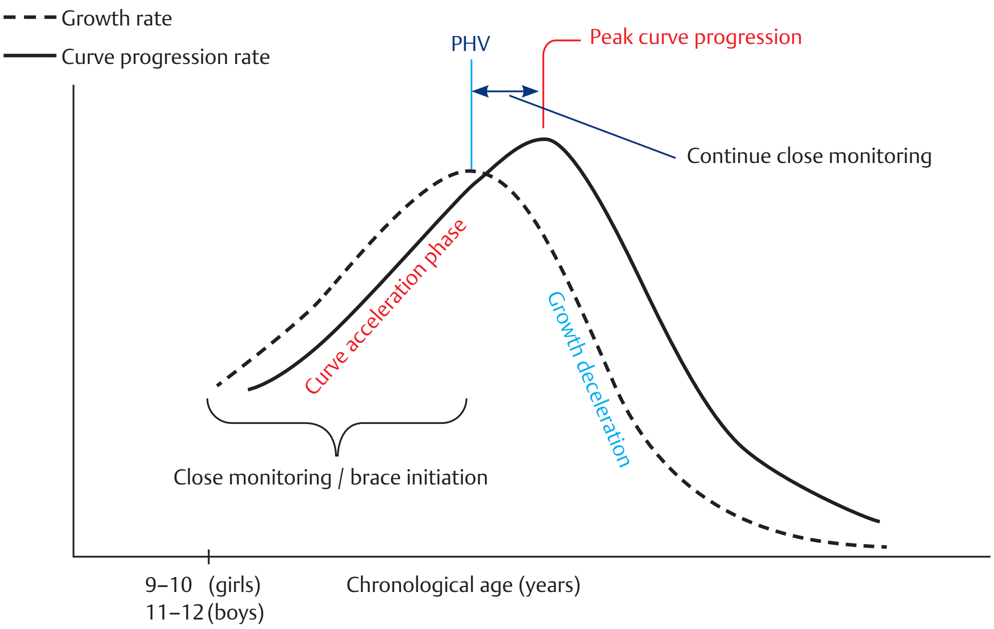


Fig. 7.1 Schematic diagram of peak height velocity (PHV) and curve progression in relation to the management of adolescent idiopathic scoliosis (AIS).

Curve progression can continue and peak even after PHV, as there can be a mismatch between the timing of peak growth and peak curve progression.[5] Close monitoring for curve progression should be continued even at the start of growth deceleration, as curve progression can still be occurring toward its peak. During the growth deceleration phase, the likelihood of curve progression is gradually reduced as growth diminishes with skeletal maturity. Curve should become stable with growth completion as indicated by epiphyseal closure.[26]

Drawbacks of clinical maturity assessment

Clinical maturity assessment is useful for treatment consideration but have limited usefulness. Chronological age is not an accurate indicator of the pubertal growth stages of the patient as every child enters pubertal growth spurt at different ages. There are also racial disparities in the timing of puberty depicted by chronological age.[27,28] Another clinical maturity parameter frequently used for AIS is the onset of menarche for girls. Menarche can only provide retrospective information that peak growth has already passed, as linear growth slows significantly post menarche with the elevated level of estrogen stimulating epiphyseal growth plates closure.[16] Girls who experienced menarche are considered as having a gradual decrease in the risk of curve progression.[29] However, some girls have delayed menarche,[26] making the onset of menarche less accurate in indicating the timing of PHV and limiting its use in guiding treatment for AIS. Secondary sexual characteristics can be useful parameters for maturity assessment. The onset of puberty can be indicated by the first appearance of pubic hair, swelling of the testes, or budding of the nipples.[9] However, its ability in predicting the timing of PHV is guarded, and it highly correlates with the patient's nutritional status and family history of delayed puberty. Its use becomes less popular as the secondary sexual characteristics cannot be assessed easily in the clinic. Also, the measurements of body height and arm span are commonly used growth parameters to assess maturity status. There are issues about inaccurate standing and sitting body height due to loss of trunk height caused by the spinal curvature. Such height loss is better documented in sitting height[30] than standing height as whole body height measurement including lower limbs suffers less inaccuracy in proportion. The problem of scoliosis affecting body height can be avoided with the use of arm span.[31] Unfortunately, the growth rates based on body height and arm span from previous visits can only reflect the growth that had already occurred, and they can only be observed for the trend of future growth rather than being predictors of maturity. Hence, their role in AIS management is limited. Foot length or shoe sizes are clinical parameters with evidence that their course of growth can be indicators for the timing of pubertal growth spurt.[32–34] However, there is limitation of recall bias of shoe sizes by the parents, and the reliability of measuring foot length or using shoe size in maturity assessment in the clinic remains unknown.

Bone age assessments

Risser staging

Risser staging was developed with 200 untreated scoliosis cases in the United States in 1958, based on the ossification of the iliac apophysis.[35,36] It was first validated in 111 patients with AIS,[37] and other studies confirmed its acceptable observer reliability.[38,39] Risser staging is used as a prognostic indicator for growth assessment,[40] and is comprised of 6 stages (Risser stage 0 to 5) (**Fig. 7.2**).

Risser stage 0 was later modified by including the triradiate cartilage, based on a set of 120 pelvic radiographs from the female patients of the Bracing in Adolescent Idiopathic Scoliosis Trial (BRAIST) study.[41] This is due to the issue of Risser stage 0 including patients with a wide range of digital skeletal age scores. Risser stage 0 with triradiate cartilage which is not yet ossified is classified as Risser stage 0 −, and those with closed triradiate cartilage as Risser stage 0 +. In the study by Nault et al, Risser stage 0 + and Risser stage 1 together was demonstrated as a useful predictor of the beginning of curve acceleration phase for girls with AIS.[42]

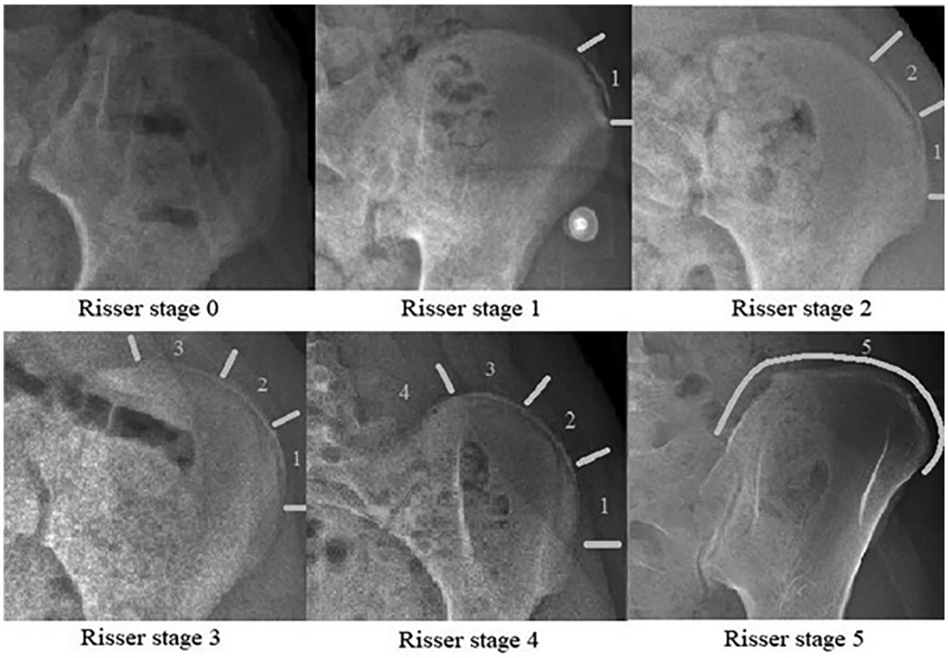


Fig. 7.2 Risser staging from 0 to 5. Iliac apophysis is not yet visible at Risser stage 0, and the iliac apophysis ossification starts to appear at the anterior region of the iliac crest at Risser stage 1. When the ossification starts to migrate halfway across the top of the iliac wing, it is defined as Risser stage 2. Risser stage 3 refers to apophysis covering three-quarters of the iliac crest, and Risser stage 4 refers to ossification crossing the iliac wing, but not fused to the ilium. Complete ossification of the iliac apophysis with fusion to the ilium is graded as Risser stage 5.

Despite being the most widely used skeletal maturity parameter and readily visible on spine radiographs, criticism of Risser staging mainly relates to the fact that two-thirds of pubertal growth occur before Risser stage 1.[43] Risser staging has poor sensitivity during the acceleration growth phase prior to PHV.[44] It lacks correlation with skeletal ages,[45] as well as predictive effect of growth potential.[46,47] Moreover, the distorted image of the iliac apophysis and the medial and lateral aspects of the apophysis superimposed over the ilium on posteroanterior radiographs can compromise reliability and accuracy of the staging, as there is only 58% agreement between the Risser stages assessed from posteroanterior and anteroposterior plain radiographs.[48] Mismatches of Risser staging with the Sanders staging and the distal radius and ulna (DRU) classification are evident, resulting in over- or underestimation of skeletal maturity.[49,50] Risser staging is not found to be any better in predicting curve progression than chronological age due to its inaccuracy, and it should not be used in place of a hand and wrist radiograph.[51]

Tanner-Whitehouse staging

The Tanner-Whitehouse (TW) staging method was developed in 1959 based on 2,600 British children without scoliosis by J.M. Tanner.[52–54] It involves a scoring system by assessing specific ossification centers of 20 selected bones in the hand and wrist. These 20 bones for ossification analysis are the radius, the ulna, the short bones, and the carpal bones. The concept is that individual hand and wrist bones mature at different rates, and each bone is assigned with a score based on the maturation stage defined by specific criteria. There are 8 stages for each bone of the hand and wrist labelled A to H, or 9 stages especially for the radius, labelled A to I (**Fig. 7.3**).

Each stage is assigned a specific score according to the maturation stage and there are specific differences between gender. The sum of these scores results in a skeletal maturity score that can be converted into skeletal age. The system has undergone modifications into TW2 and TW3.[55] The TW2 method was developed in the United Kingdom, involving three components: the scores of 20 bones, the radius, ulna, and selected metacarpals

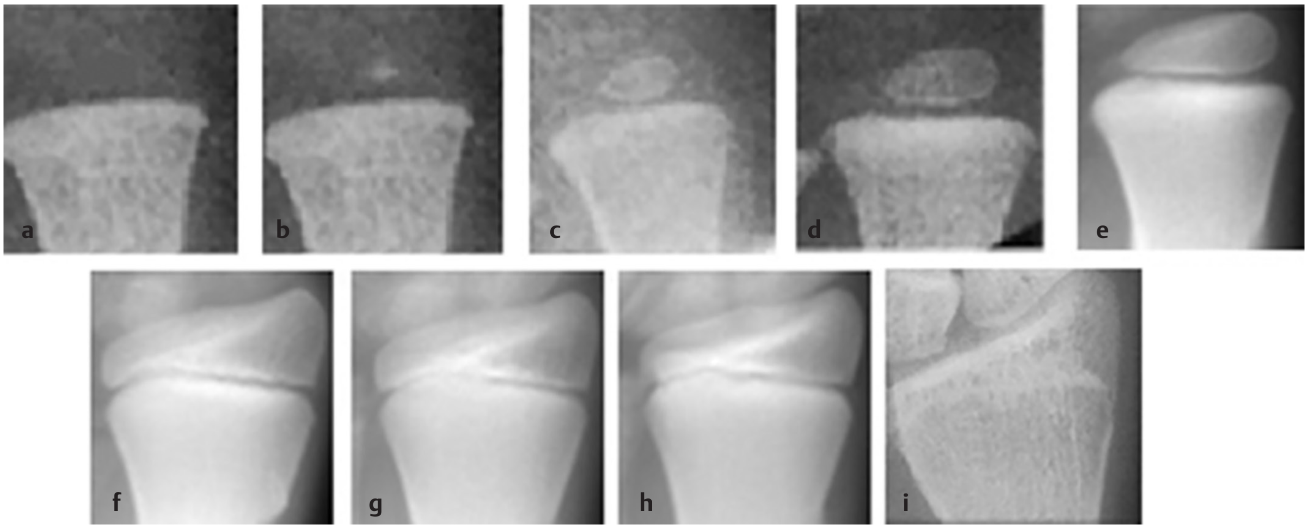


Fig. 7.3 (a–i) Tanner-Whitehouse staging: Skeletal maturation stages A to I (radiographic appearance of radius here as an example). Stage A indicates that the epiphysis (or bone) is not present, whereas Stage I represents full skeletal development (complete fusion), except some elements like the ulna. Stage H (commencing fusion) is the last stage to score.

and phalanges (RUS) score, and the carpal score (including all carpal bones except for the pisiform). For TW3, only the RUS bones are considered for assessment, and it can estimate younger bone age (**Fig. 7.4**).

TW3 was found to be more accurate than the TW2 method in white children. Both TW2 and TW3 methods were more accurate than the Greulich and Pyle in Caucasians and Mongoloids,[56] and were demonstrated to be more reliable.[57] Various systems of the TW staging method have been validated and studied in different scoliosis cohorts. The TW3 RUS score had strong correlation with the curve acceleration phase in girls in the study by Sanders et al,[20] who later developed the Sanders staging with the TW3 RUS descriptors but eliminated the maturation stages of the radius and ulna. Kobanawa et al had investigated the use of TW2 in the girls with AIS and found that bone ages of the immature (apophyses without an apparent narrowing of cartilage), curve progression group distributed between 11.7 and 13.9 years, whereas those without curve progression distributed mainly over 13.1 years.[58] One recent study revealed that the simplified TW3 method had lower observer reliability than the DRU classification.[59]

The advantage of the TW staging method is that each bone segment is evaluated by comparing to a standard set of bones at different stage of maturation. The comparison against the criteria set can minimize interrater variability. The application of the TW staging is, however, limited by the accuracy of the radiographic appearance of the hand and wrist. Proper positioning of the hand is crucial as rotation of the radius and ulna can alter radiographic appearance of the epiphyses.[60] The effects of poor exposure can also lead to inaccuracies of assessment and difficulty in image interpretation. The lack of consistencies of repeated rating among observers can be a concern as well.[60] TW3 was found to have an underestimation of the age by an average of 5 months in girls in the United Kingdom.[61] The TW staging method was found to be accurate in predicting the adult height in normal-growing athletic boys,[62] but not specifically for patients with spinal deformity. Also, the skeletal maturity scoring system of the TW staging method can be time-consuming.

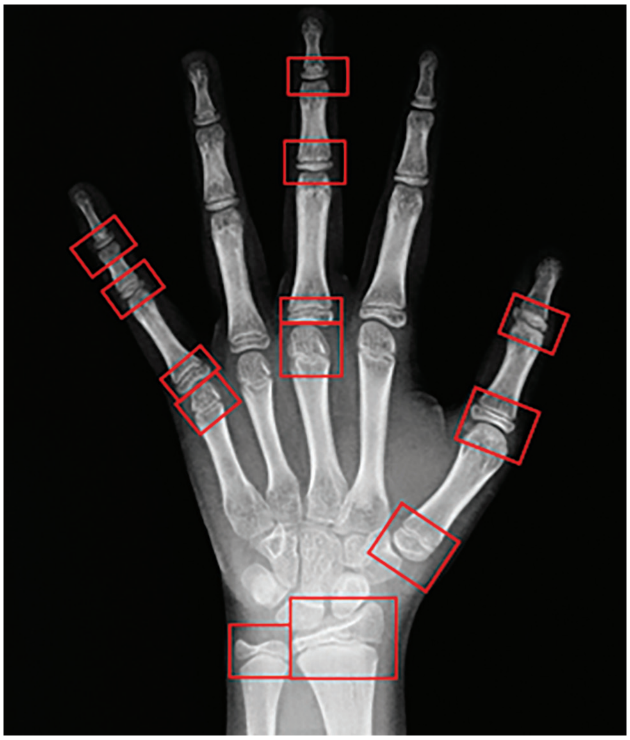


Fig. 7.4 Measurement points of the Tanner-Whitehouse III method: Radius; ulna; metacarpals I, III, and V; proximal phalanges I, III, and V; middle phalanges III and V; distal phalanges I, III, and V.

Greulich and Pyle

The Greulich and Pyle method was derived from a longitudinal study conducted during 1931–1942 by T.W. Todd, and it was later introduced in 1959 by utilizing the hand-wrist radiographs from about 1,000 white upper-middle class American of North European ancestry in the Bolton-Brush study to form an atlas.[63,64] It consists of two standard templates for the males and females with 31 and 27 radiographic images respectively. The assessment involves the clinician initially choosing the similar image from the standard, followed by assigning the corresponding bone age for individual segments in an ordered sequence that requires an in-depth evaluation of each bone segment.[65] It is widely used due to its simplicity and ease of clinical application. The main advantage is that the assessment is performed by matching and visual inspection.[57] But Greulich and Pyle method has greater interobserver variation than the TW staging method.

Despite its use for bone age determination worldwide, there are concerns of whether the Greulich and Pyle atlas can be used for patients of different ethnicities as the atlas was developed based on white American as a reference population.[66] Also, its wide spacing of skeletal age may make Greulich and Pyle system less sensitive for PHV.[20] Skeletal age assessment by the Greulich and Pyle atlas may be difficult for the growth acceleration phase, from the age of 11 to 13 years for girls and from 13 to 15 years for boys.[9] Some criticism was also reported in regards to the application of the Greulich and Pyle atlas, that children and adolescents may be experiencing faster growth rate toward maturity nowadays as a result of nutritional improvement and socioeconomical affluence, as compared to the time when the atlas was developed.[67,68] Thus, the estimation of growth status and maturity may be compromised.

The Greulich and Pyle method has been commonly used in clinical practice, including bone age estimation for patients with scoliosis. However, the system lacks as strong a correlation with the curve behavior of idiopathic scoliosis as other indices like the Sanders staging.[25]

Distal radius and ulna classification

The DRU classification was developed in 2013 by Luk et al based on 150 female patients with AIS of Chinese descent from a cohort of >1,600 screened.[69] This skeletal maturity system is based on the process of epiphyseal fusion of the distal radius and distal ulna, and it refines the TW3 RUS classification. Cheung et al then simplified it and investigated its observer reliability finding strong to near-perfect intraclass correlation.[70] The index consists of 11 radius grades (R1 to R11) and 9 ulnar grades (U1 to U9) (**Fig. 7.5**), with advancing stages observing the progressive changes of the relative sizes of epiphysis and the metaphysis, capping of the epiphyses, and narrowing to complete ossification of the physes.

The DRU classification has the advantage of focusing on the distal radius and distal ulnar physeal maturation

Radius grades	**Radiographic characteristics**	**Schematic diagram**
R1	Epiphysis appears as single or multiple spots	
R2	Distinct and oval-shaped epiphysis	
R3	Maximal diameter of the epiphysis is more than half the width of the metaphysis	
R4	Double line at the distal border of the epiphysis representing the palmar and dorsal surface	
R5	Thickened white line shaped as a triangle in the epiphysis; width of the epiphysis not as wide as the metaphysis	
R6	Epiphysis is as wide as metaphysis using a vertical tangential line. No capping or narrowing of the physis	
R7	Epiphysis capping on the medial side but not on the lateral side. Irregular narrowing of the physis can be seen.	
R8	Epiphysis capping on both medial and lateral sides. The physis at the medial and lateral ends is wider than the center.	
R9	Beginning to fuse at the central physis or it appears blurred	
R10	The physeal line is completely obliterated, forming a sclerotic line. A notch is still visible at the medial or the lateral end of the growth plate.	
R11	Complete fusion of the physis with the metaphysis at both the lateral and medial ends. A growth plate scar may still be visible.	

Ulnar grades	**Radiographic characteristics**	**Schematic diagram**
U1	The epiphysis appears as single/multiple spots	
U2	A round-shaped epiphysis	
U3	The epiphysis is at least half the width of the metaphysis	
U4	The styloid is visible on the medial end of the epiphysis, which is not as wide as the metaphysis	
U5	Epiphysis width up to the metaphysis based on a vertical tangential line	
U6	Medial epiphysis beyond the metaphyseal vertical tangential line with rounding of the medial epiphysis to form a smooth curve with metaphysis	
U7	Narrowing or fusion of the medial physeal plate	
U8	Medial growth plate has > 50% fusion. The unfused part is just proximal to the styloid process.	
U9	Complete physeal fusion with a growth plate scar may still be visible.	

Fig. 7.5 Distal radius and ulna classification.

progression, which spans the whole period of skeletal growth, and they are the last ones to fuse.[69] The gradings tend to spread more evenly throughout the pubertal phase in terms of bone age gap interval between each stage. This skeletal maturity index is simple and reliable to use, and it originates from the idiopathic scoliosis patient cohort. The DRU classification has been shown to depict peak skeletal growth at radius grade (R) 6 and ulna grade (U) 5, and the beginning of growth plateau at R9 and U7 in 777 patients with AIS,[22] as well as predict curve progression in a large-scale study of 513 patients.[21] The DRU classification has been validated in the idiopathic scoliosis populations in the Greater China,[71,72] Japan,[59] and the United Kingdom,[73] and in comparison with other established maturity index such as the Sanders staging.

The efficacy of the DRU classification in various clinical applications have been studied. It can be utilized for predicting the final body height in girls with AIS when they were first presented,[74] taking the curve magnitude into consideration. The gradings can be used for predicting curve behavior,[71] thus determining whether bracing is indicated.[75] In addition, the ulnar grading is useful in refining Sanders stage 7 in guiding the timing of brace weaning.[76] This relates to the characteristic of this skeletal maturity index being able to differentiate the beginning of the growth plateau prior to reaching complete skeletal maturity. Interestingly, the DRU classification reveals that there is a time lag between PHV and peak curve progression by about one grade (**Fig. 7.6**), or by a period of approximately 7.2 months. The period of possible curve progression risk can extend to approximately 1.5 years after peak growth.[5] These findings serve to remind clinicians that vigilant monitoring of the curves should continue well beyond PHV.

Sanders staging

The Sanders skeletal maturity staging system was developed in 2008 as a simplification of the digital method using the TW3 RUS descriptors and the Greulich and Pyle system.[25] Interestingly, it was developed based on a relatively small number of only 22 American girls with idiopathic scoliosis. The system consists of 8 stages (here referred to as Sanders Stage [SS]1 to SS8), describing the progressive growth until complete fusion of the epiphyses of the digits of the hand and at the distal radius and ulna. Radiographic illustrations of the morphological changes of the metacarpals and phalanges are presented in **Fig. 7.7**.

A SS7b grade has been recently proposed for the purpose of more precise timing of brace weaning.[76] By incorporating ulnar grade 8 of the DRU classification (ie, medial physeal plate of the distal ulna has >50% fusion, with the unfused part being just proximal to the styloid process) into SS7, forming the SS7b, the risk of curve

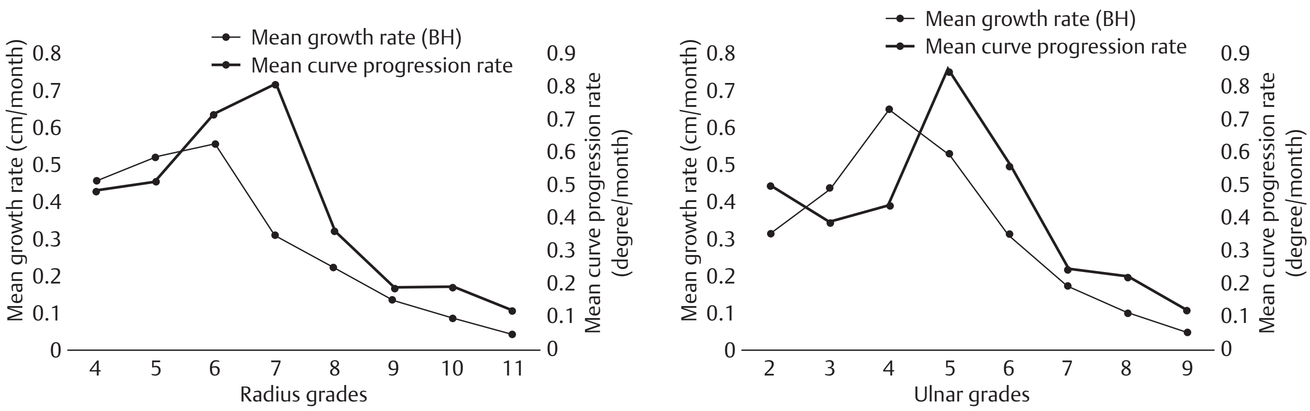


Fig. 7.6 Lagging of peak curve progression from peak height velocity (PHV) as assessed by the radius and ulnar grades of the distal radius and ulna (DRU) classification.

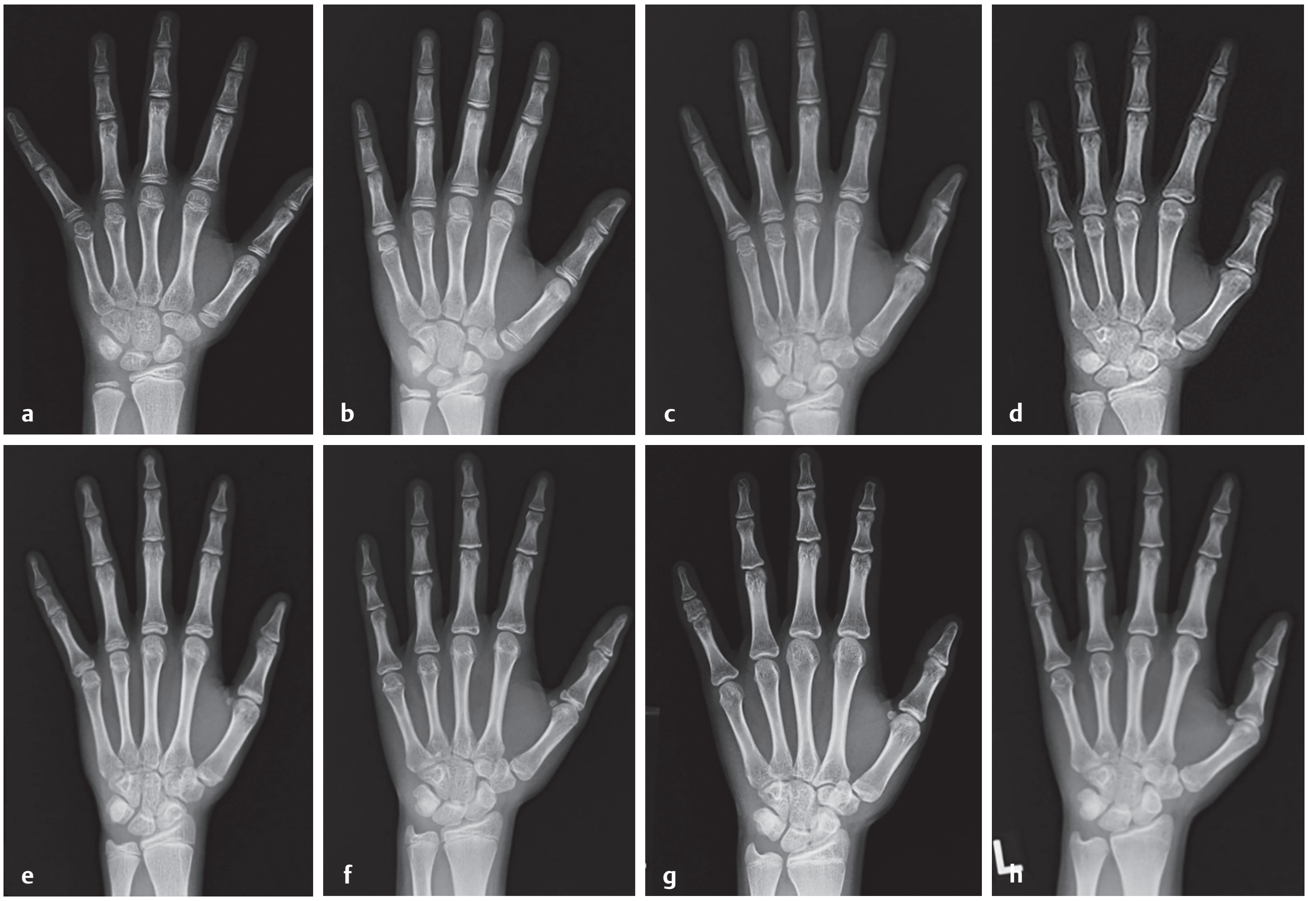


Fig. 7.7 (a–h) Key radiographic features of Sanders stages (SS). SS1: All of the digital epiphyses are not covered. SS2: All of the digital epiphyses are covered. SS3: Most epiphyses cap their metaphyses. In the metacarpals, the second through fifth heads are wider than the metaphyses. The epiphyses cap the thumb metacarpal. SS4: Distal phalanges begin to have physeal closure. SS5: All distal phalangeal physes are closed. SS6: Some of the proximal or middle phalangeal physes are closing while all of the distal phalangeal physes are closed. SS7: All of the physes are closed, except for those of the distal parts of the radius and ulna. SS8: All the physes are closed.

progression remains minimal after brace weaning for major curves of <40°.[76]

In a series of 22 girls with idiopathic scoliosis, Sanders et al found that PHV and curve deterioration can be identified by the capping phase of the epiphysis of the phalanges.[20] Sanders staging was then later validated and shown to be predictive of curve progression in 161 patients.[19] However, there are a few limitations of using the Sanders staging, especially the inappropriate spans of the stages which may affect the precision of growth assessment and miss important pubertal growth landmarks. There are wide spans between SS1 and SS3, and clustering and uneven span between SS4 and SS6 with each grade advancing within 6 months of the previous grade.[25,77,78] Moreover, the ambiguity of some of the descriptions of the Sanders stages, such as the extent of closure of the proximal and middle phalangeal physes in SS6, makes the classification prone to high interobserver variations.

The thumb ossification composite index

The thumb ossification composite index (TOCI) was developed in 2017, based on 125 girls of Chinese descent with AIS. It assesses the growth status of a child by staging the process of ossification of the thumb epiphyses of the distal phalange, the proximal phalange, and the adductor sesamoid bone. There is a total of eight TOCI stages with TOCI stage 1 or 2 referring to the absence of the adductor sesamoid, and TOCI stage 3 indicating first appearance of the ossified adductor sesamoid. When the ulnar corner of the thumb proximal phalangeal epiphysis starts to cap, TOCI stage 4 is reached. TOCI stage 5 is the timing of PHV, when advanced capping along the ulnar corner of the proximal phalangeal epiphyses in the thumb occurs.[79] TOCI stage 6 indicates the descending growth phase when the distal phalangeal physis completely fuses. TOCI stages 7 and 8 refer to the partial and complete fusion of the proximal phalangeal epiphysis respectively. PHV occurs between TOCI stages 4 and 5. Currently, there is lack of evidence of the TOCI system with curve progression prediction; however, its stage-to-stage correlations with Sanders stages were observed locally in Hong Kong and in a Japanese cohort.[80,81]

Olecranon

The Sauvegrain method for the assessment of skeletal age was developed in 1962 and it has been used in France and Belgium for decades.[82,83] It utilizes the ossification centers at the elbow and is based on a 27-point scoring system. The simplified olecranon method was derived from the Sauvegrain method in 2005.[84] It focuses on grading the olecranon apophysis, and this allows skeletal maturity to be assessed in a regular 6-month interval during the PHV phase.[83] It involves five radiographic appearances of typical characteristics of the olecranon during pubertal growth, in advancing order: two ossification nuclei, a half-moon image, a rectangular shape, beginning of fusion, and complete fusion (**Fig. 7.8**).

The midpoint of the accelerating growth phase is indicated by the rectangular shape of the olecranon (stage 3). Complete olecranon physeal fusion marks the end of the PHV and it signifies the start of decelerating height velocity.

The advantages of this maturity index are its simplicity and ease of clinical application, its design for 6-monthly assessment of skeletal maturity which is suitable for the follow-up period of idiopathic scoliosis patients, as well as its coverage of prepubertal stage and early puberty. The simplified olecranon method is particularly useful for bone age assessment during the first 2 years of puberty, at which the thoracic curves tend to progress more.[9] The olecranon method was first validated with 200 boys and girls with idiopathic scoliosis in France.[83] During Risser stage 0, the olecranon maturation could provide a reliable prediction of curve progression risk in patients with idiopathic scoliosis, as found in the cohort of 372 patients.[23] However, the olecranon method has limitations as it can only cover the growth spurt partially. As the period beyond the end of PHV is still important for AIS management like bracing and the timing of surgical correction, the use of another skeletal maturity index is required after the olecranon apophysis has completely fused.[77]

Proximal humerus

The proximal humerus ossification system (PHOS) focuses on the peripheral changes of the proximal humerus.[85] It was developed based on a subset of 94 subjects from the Brush inquiry study, which was a longitudinal collection of growth and developmental data from a heterogenous group (racial and socioeconomic) of healthy children and adults in the United states

Fig. 7.8 Morphological development of the olecranon in the form of five radiographic images defined in the simplified olecranon method.

from 1926 to 1942.[86] It has five stages, ranging from an incompletely ossified lateral epiphysis of the proximal humerus (stage 1) to the complete fusion of the lateral half of the physis (stage 5) (**Fig. 7.9**).

The PHOS was demonstrated to have strong correlation with the age of PHV and the percentage of growth remaining.[85] The advantage is the visibility of the proximal humerus in most spine radiographs, but the position for imaging without distortion can be challenging due to the current standards of arm positioning for radiographs (ie, fists on clavicles but arms slightly forward for better visibility of the sagittal alignment of the spine[87]). Currently, the use of the PHOS in idiopathic scoliosis is relatively limited. It was one of the parameters used in the predictive model for PHV in a validation study of 216 patients with AIS, and in the context of its relationship with the Sanders staging.[88] Recent study focuses on the role of PHOS in the management of AIS and it is found useful as a skeletal maturity indicator for brace weaning, as weaning at PHOS stage 5 had no postweaning curve progression for major curves of <40°.[89]

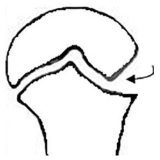
PHOS Stage	Radiographic characteristics of the proximal humerus	Schematic illustration
1	An oblique lateral margin at the lateral epiphysis whose ossification is incomplete	
2	A curvilinear lateral margin at the lateral epiphysis with increased ossification	
3	The lateral half of the physis is open without obvious fusion—the lateral margin of the epiphysis is as wide as the metaphysis	
4	The lateral half of the physis thins and begins partial fusion	
5	Complete fusion at the lateral half of the physis.	

Fig. 7.9 The proximal humerus ossification system (PHOS).

Proximal femur

As the current standard of arm positioning can impede or distort the viewing of the proximal humerus ossification, the convenient viewing of the ossification centers at the proximal femur is possible in EOS® (EOS Imaging, Paris, France) whole spine radiograph. The proximal femur maturity index (PFMI) is a recently developed skeletal maturity index based on the radiographic appearance of the proximal femur, the greater trochanter, and the triradiate cartilage. It involved a cohort of 104 patients of Chinese descent with idiopathic scoliosis, with longitudinal growth data and their corresponding 780 femur gradings.[90] The PFMI consists of 7 grades from grade 0 to 6 with advancing skeletal maturity (**Fig. 7.10**).

PFMI grade 3 indicates peak growth, whereas grade 6 is suggestive of growth cessation.[90] The PFMI gradings have strong correlations with other skeletal maturity indices like Risser staging, Sanders staging, and DRU classification in patients with idiopathic scoliosis. Currently, prediction of the risk of curve progression by the PFMI is not yet available, and how the PFMI can be used in guiding treatment in idiopathic scoliosis and other orthopedic pathologies should also be studied in the future.

How should one use these different maturity parameters

The use of a single index alone is rarely adequate for skeletal maturity assessment; rather the continuum of the growth period necessitates the use of maturity measures in conjunction.[77] The interrelationships and cross-referencing of skeletal maturity measures can benefit in terms of precision and accuracy of indicating pubertal landmarks,[50] thus possibly enhancing treatment effectiveness as the timing of intervention (its prescription

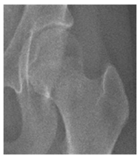
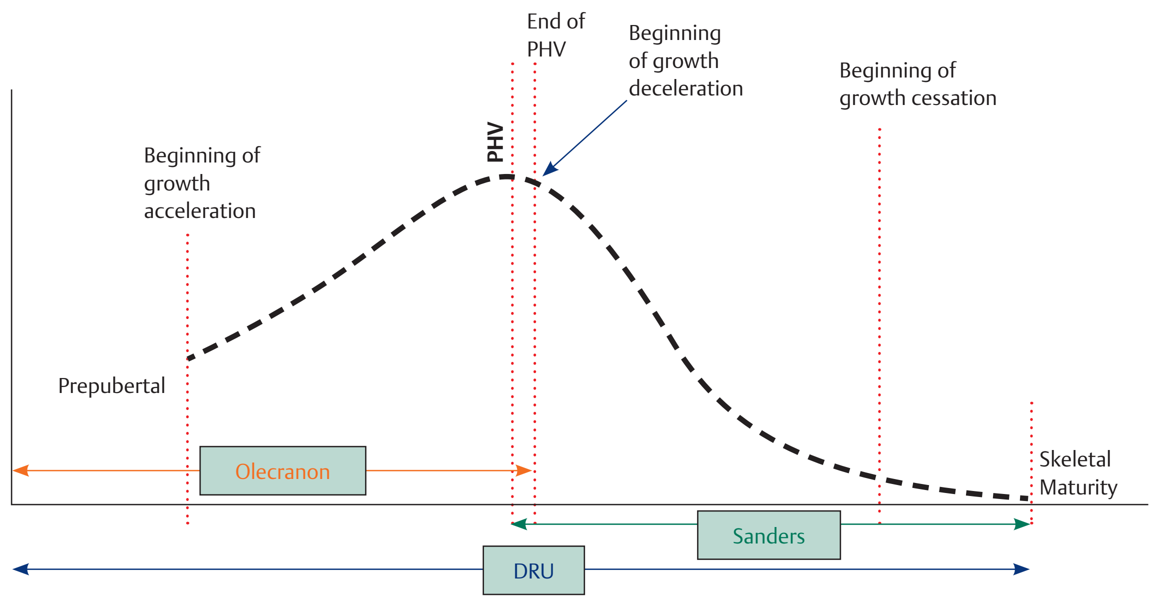
Femur Grade	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Stage	Pre-adolescent	Acceleration phase	Pre-peak	Peak growth	Post-peak	Growth deceleration	Maturity
Triradiate cartilage	Open	Open	Open	Open/closed	Closed	Closed	Closed
Femoral head	Epiphysis smaller than metaphysis	Epiphysis larger than metaphysis	Lateral physeal beaking	• Medial physeal beaking with lateral side already beaking or closed • Oblique/curved physis	Narrowing of the physeal plate or partial fusion	Closed physis with scar still can be seen	Complete fusion
Greater trochanter	Round-shaped	Tapered in shape	Triangular-shaped	Trochanteric notch or double contour line over piriformis fossa	Middle of physis is fused	Complete fusion	Complete fusion
Schematic diagrams							
Example of radiographic appearance							

Fig. 7.10 The scheme of the proximal femur maturity index.

and cessation) can be crucial. This is particularly the case in patients with leg length discrepancy and idiopathic scoliosis,[91] as pubertal growth prior to the PHV occurs predominantly in the limbs first followed by the spine.[92]

Each maturity parameter has its respective characteristics and the period of growth the skeletal maturity index covers. This is due to the different timing of physeal closure at various ossification centers, like the thumb epiphyses mature slightly earlier than the other digital epiphyses,[72] which fuse earlier than the distal radial and ulnar epiphyses in sequence. The DRU classification has the advantage of having more gradings available for assessment from prepubertal growth phase until the end of puberty with full skeletal maturation. The simplified olecranon method is also reliable in assessing prepubertal growth but only until the end of PHV, whereas Sanders staging has issues with uneven spans between gradings at multiple timepoints of pubertal growth. **Fig. 7.11** provides a recommendation of the use of skeletal maturity indices in combination for the period of prepubertal growth to skeletal maturity.



Prepubertal	Beginning of growth acceleration	PHV	End of PHV	Beginning of growth deceleration	Beginning of growth cessation	→	Skeletal maturity
Olecranon 1 < R3, <U3	Olecranon 1, R3, U3 (corresponding SS1)	Olecranon 4, R6, U5, SS3	Olecranon 5, R7, U6, SS4	R8, U7, SS5	R9, U7, SS6/7	SS7, U8 (SS7b)	R11, U9, SS8

Fig. 7.11 Recommended concurrent use of skeletal maturity indices for different stages of growth. (PHV, peak height velocity.)

Prepubertal and acceleration phase of growth

The DRU classification and the simplified olecranon method allow effective assessment of skeletal maturity at the prepubertal phase, which the Sanders staging does not. The simplified olecranon method offers more details than the Sanders staging during the 2 years of accelerated growth phase.[93] For the DRU classification, this is also evident as SS1 corresponded to only the radius gradings of R3 to R5 and ulnar gradings of U3 in patients with idiopathic scoliosis[72,77] (**Fig. 7.11**). Thus, grades R1, R2, U1, and U2 of the DRU classification are available for growth assessment in younger patients at the prepubertal phase. Both Chinese and British studies of the DRU classification also report that very immature radius and ulnar grades are not used in their AIS cohorts.[73,90] Those early grades of the index are readily available if a younger child is presented not only for early onset scoliosis, but also for other orthopedic pathologies, such as patients requiring epiphysiodesis for limb length discrepancy.[94–96] The DRU classification provides comprehensive coverage of the whole growth period, equipping clinicians with gradings in more detailed differentiation. The DRU grades, together with the simplified olecranon stages, provide coverage of infantile and juvenile growth for the much younger and immature patients.

Peak growth/peak height velocity

In order to ensure satisfactory assessment of the skeletal maturity and growth potential without disruption at PHV and up to immediate post-peak, the use of the simplified olecranon method, DRU classification, and Sanders staging in conjunction is deemed necessary. Olecranon stage 4 (the beginning of fusion of the olecranon apophysis) occurs at PHV,[97] and its complete fusion (stage 5) represents the end of PHV.[98] Hence, the introduction of the Sanders staging near the PHV alongside DRU gradings enables both indices to continue skeletal maturity assessment until growth cessation. A previous study has demonstrated that SS3, R6, and U5 are indicative of peak growth in girls, whereas R6 is relatively more effective in indicating peak growth than SS3 and U5 in boys.[50]

Beginning of growth cessation

The DRU classification has evidence that R9 U7 represents the beginning of growth cessation with an average growth rate of standing body height (or arm span) of ≤0.15 cm/month.[22] By this criteria of growth rate, SS6/SS7 and U7/U8 were able to indicate the beginning of the growth plateau better.[50] As discovered by Cheung et al,[76] SS7 (defined as all of the digital physes are closed except for those of the distal radius and distal ulna) can be better differentiated by U8, forming the SS7b, which may be a suitable time to consider brace weaning for major curves of <40° without waiting for complete skeletal maturation (**Fig. 7.12**).

Fig. 7.12 The use of both Sanders staging and DRU classification for more precise timing of brace weaning of small curve was proposed at SS7b (ulnar medial physis > 50% fusion of the medial growth plate).

A skeletal maturity measure which can indicate the beginning of growth plateau prior to full maturity would be beneficial if growth plateau indicates very little or no risk of curve progression. This can aid in decision-making of continual bracing, gradual weaning, or complete weaning of brace wear, given the consideration of curve magnitude and curve progression at that point in time.[76]

A summary of the possible clinical application of skeletal maturity indices is presented in **Table 7.2**. Currently, there is a lack of research in TOCI, PHOS, and PFMI about their relationship with curve progression and their application in treatment decision-making.

Future developments

For any growth assessment classification to be meaningful, it should be precise in identifying the different phases of growth—preferably from infancy to adulthood, simple to remember, and easily applied in a busy clinic with low interobserver variation. In the situation of idiopathic scoliosis management, such classification should be able to accurately prognosticate curve progression and thus assist the clinician in treatment decision-making.

Current constraints of growth assessment methods

The limitation is that *none* of the skeletal maturity classifications currently being used can in isolation fulfill the above criteria and is useful for all the pediatric orthopedic conditions.

A skeletal maturity index which is based on an ossification center whose fusion is completed within pubertal growth spurt, or a grading system that fails to demonstrate the pubertal acceleration–deceleration growth pattern poses concerns. Also, classification systems involving many physes can be too cumbersome in a busy specialist clinic. With conditions like leg length discrepancy, the determination of skeletal age in young children by the elbow radiographs is limited as the ossification center at the elbow does not exhibit specific morphologic characteristics and changes[99,100] until later (girls: between 10 and 13 years of age; boys: between 12 and 15 years). The use of Sanders staging is also limited when

Table 7.2 Recommended use of skeletal maturity indices and possible clinical situations

Pubertal growth phase	Possible gradings of maturity	Clinical situations and possible decisions	
Prepubertal	Olecranon stage 1, <R3, <U3	Major coronal Cobb angle < 25° **Observation**	Major coronal Cobb angle ≥ 25° Less than 1 year post-menarche **Initiation of bracing**
Beginning of growth acceleration	Olecranon stage 1, R3, U3, SS1		
PHV	Olecranon stage 4, R6, U5, SS3		
End of PHV	Olecranon stage 5, R7, U6, SS4		**Continue bracing** (or brace initiation for large curve magnitude at clinician's discretion)
Beginning of growth deceleration	R8, U7, SS5		
Beginning of growth cessation	R9, U7, SS6/7		
	SS7, U8 (SS7b) →		Major coronal Cobb angle < 40° and no bodily growth and post-menarche for 2 years **Brace weaning**
Skeletal maturity	R11, U9, SS8		**Observation**

Abbreviation: PHV, peak height velocity.

the onset of the PHV and the timing for achieving 90% final height correlates with the time when SS2 advances to SS3, with SS2 and SS3 occurring immediately before and immediately after PHV, respectively.[8] This prompts the concurrent use of another index such as the DRU classification whose radius or ulnar gradings can refine the period and indicate PHV more effectively.

Future direction

Considering the current limitations of the present skeletal growth classifications in use, we should strive to develop one unified classification by combining the strengths of each of them (**Fig. 7.13**).

In order to achieve the required criteria, a new skeletal maturity index should have specific characteristics (they intertwine) which stem from the strengths of the existing classifications:

- The selection of a growth center:
  A growth center that can cover the whole period of growth should be chosen for developing the new index. Ideally, the integrated skeletal maturity grading should cover the entire period of growth from infancy to adulthood. This comprehensive coverage can avoid the need of using different maturity indices at different stages of pubertal growth.
- The visibility of the growth center:
  To minimize radiation exposure, such growth center should be conveniently visible on the radiographs of the pathology under consideration, eg, the shoulder or hip region for AIS. Since the hand radiograph provides the most accurate skeletal maturity assessment, the inclusion of the hand in the EOS imaging of spine can be further developed.

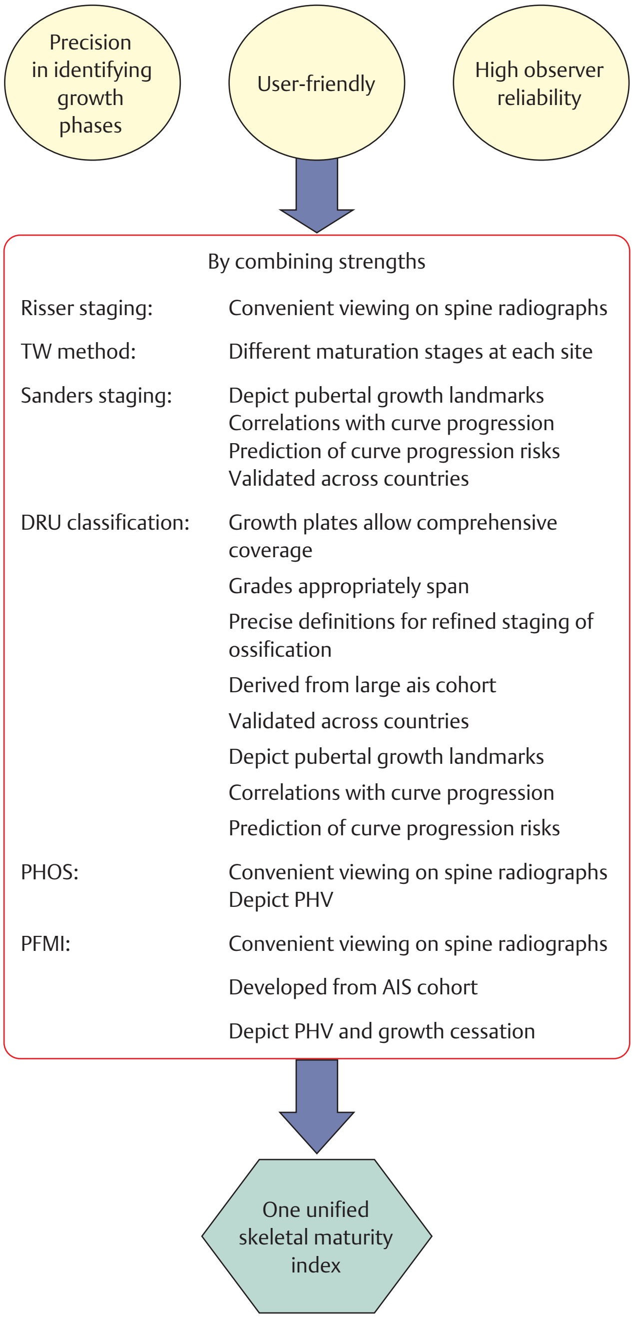


Fig. 7.13 Conceptual diagram for future development of skeletal maturity measure for idiopathic scoliosis. (DRU, distal radius and ulna; PFMI, proximal femur maturity index; PHOS, proximal humerus ossification system; PHV, peak height velocity; TW,Tanner-Whitehouse.)

For patients with juvenile leg length discrepancy, the gradings of the hip may be more appropriate.

- Sensitivity of the gradings:
  Span of appropriate intervals between the gradings is important. A good time spread between the grades can improve sensitivity. Refined stages can ensure that important pubertal landmarks will not be missed.
- Clinical relevance:
  The gradings of the skeletal maturity measure should be clinically relevant to the pathology. For example, in AIS, a DRU classification of R6U5 denotes peak height growth with peak curve progression occurring at the following 9 months, and R10U9 signifies very low risk of further curve deterioration.
- User-friendliness:
  For a maturity measure to be user-friendly, the distinctive features of each grade should be explicit and without ambiguity. This makes the grading easier to memorize and ensures a lower interobserver variation.

Conclusion

The importance of accurate and effective skeletal growth assessment in patients with AIS cannot be emphasized enough. With an overview of the available skeletal maturity indices, the DRU classification appears to be most capable of providing a good coverage of all the phases of the pubertal growth period, with validation in both the Asian and European populations in identifying peak growth and growth cessation. To further improve the efficacy of the DRU classification, we propose that it could be used in conjunction with the simplified olecranon method and the Sanders staging. This may increase the precision of the skeletal maturity assessment, with the aim of optimizing the prognosis of scoliosis and the intervention strategy.

Key points

- Peak curve progression occurs after the peak height velocity.
- Despite being the most widely used skeletal maturity parameter, Risser staging is often found to be inaccurate in assessing growth.
- The DRU classification spans the entire period of skeletal growth. R6U5 indicates the PHV and R9U7 indicates growth cessation.
- Brace weaning is recommended at Sanders stage 7b.
- Use of more than one index is recommended for more precise assessment of growth.

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