January 2019

Ossification Of The Phalanges Of The Foot And Its Relationship To Peak Height Velocity And The Calcaneal System

Mekka Garcia

Ossification of the Phalanges of the Foot and its Relationship to Peak Height Velocity and the Calcaneal System

A Thesis Submitted to the Yale University School of Medicine in

Partial Fulfillment of the Requirements for the Degree of Doctor of

Medicine

By

Mekka R. Garcia

2019

Abstract

Background: There are multiple skeletal maturity grading systems, but none of them utilizes the phalanges of the foot. To minimize radiation, it would be ideal if one could assess the skeletal maturity of a foot based on bones seen on routine foot x-rays, if guided growth is being considered as a treatment option, as in hallux valgus. We developed a system that in combination with the calcaneal system, can closely predict skeletal maturity and help with the timing of surgical interventions of the foot.

Methods: We selected 94 healthy children from the Bolton-Brush study, each with consecutive radiographs from age ten to fifteen years old. Using the AP view, we analyzed the ossification patterns of the phalanges and developed a six stage classification system. We then determined the Peak Height Velocity (PHV) for each subject and defined its relationship with our system. Our system was then compared to the previously established calcaneal system.

Results: We calculated an Intraclass correlation coefficient (ICC) range of 0.957-0.985 with an average of 0.975 and interclass reliability coefficient of 0.993 indicating that this method is reliable and consistent. Our system showed no significant difference between sexes, with respect to PHV, which makes it a reliable surrogate for determining bone age in pediatric and adolescent patients.

Conclusions: Our system has a strong association with the calcaneal system. It is reliable and correlated more strongly with PHV than chronological age. The system requires knowledge of the ossification markers used for each stage but is easily used in a clinical setting.

Acknowledgements

I would like to thank the Yale University StatLab and the co-authors of this work for their guidance and support.

Allen D. Nicholson[1], Afam M. Nduaguba[1], James O. Sanders[2], Raymond W. Liu[3], Daniel R. Cooperman[1]

1 Department of Orthopaedics and Rehabilitation, Yale School of Medicine, PO Box 208071, New Haven, CT 06510

2 Department of Orthopaedics, University of Rochester School of Medicine, 601 Elmwood Ave, Box 665, Rochester, NY 14642

3 Department of Orthopaedics, Case Western Reserve University School of Medicine, 11100 Euclid Ave, Cleveland, OH 44106

Table of Contents

Introduction

Skeletal maturity staging is used to determine a child's current growth velocity and growth potential. Many pediatric diseases including growth, endocrine and chromosomal disorders depend on skeletal maturity systems to assess the amount of growth that a child has remaining, whether bone age and chronological age are concordant.[1] If a discrepancy is seen, an underlying disorder may be suggested. While assessment of bone age is widely used by most pediatric physicians, current systems remain complex and traditionally involve comparing the patient's radiographs to an atlas composed of hundreds of standard images.[2-4]

First described by Todd[5], methods of evaluating "skeletal age" have become a standard in pediatrics through the Greulich and Pyle atlas.[3] The Todd and the Greulich and Pyle atlases describe a method of determining "skeletal age" from hand radiographs. These atlases made use of the Bolton-Brush study conducted in Cleveland, Ohio by Dr. T. Wingate Todd from 1926 to 1942.[3,6] This study followed the growth and development of 4,435 healthy children who had serial radiographs of the skull, left shoulder, elbow, wrist and hand, hip, knee, and foot in addition to anthropometric data such has height and weight. The Greulich and Pyle hand atlas grouped the children of the Bolton-Brush study by sex and chronological age and then by the "average" appearance of the bones of the hand for each age group.[3] The atlas involves comparison of hand radiographs to references in the atlas to establish the "skeletal age" of a child and remains one of the most commonly used systems. Given that males and females mature at different chronological ages, the definition of skeletal age as defined by

Greulich and Pyle becomes problematic.[7] Another issue with the Greulich and Pyle atlas and other similar atlases is the primarily white demographics of the children used for the database.[8-10] However, many studies have shown that the Greulich and Pyle atlas is generally applicable to modern children although less so around puberty.[7,10] Moreover, the atlas has been shown to yield a large inter-observer error.[35]

Developed in 1975, the Tanner-Whitehouse II (TW-II) method assesses skeletal maturity using radiographs of the hand.[11] Since Tanner incorporated the concept of peak height velocity into the TW-II method, there have been several studies showing that skeletal maturity is more closely related to the timing of PHV than chronological age.[12-16] The Tanner-Whitehouse method established twenty regions in the hand, each divided into distinct morphologic stages. Based on the appearance of each ossification centers and the sex of the child, a score is assigned to each region and then added for an overall maturity score. In 2001, Tanner updated his skeletal maturity system to include population growth charts of modern children with the morphological grading staying the same. This system, Tanner-Whitehouse III (TW-III), requires scoring of multiple ossification centers and access to complex scoring tables. The complexity of the TW-III can cause significant inter-rater variability.[17]

The Sanders method is derived from the Greulich and Pyle method as well as the TW-III atlas and uses a series of eight reference descriptors to evaluate maturity and has been used to determine the prognosis of adolescent idiopathic scoliosis (AIS) curve progression.[7] Using the Sanders hand scores and AIS curvature, Sanders estimated the likelihood of AIS curve progression that would require surgery (>50 degrees) by following twenty-two girls with AIS for two years through their growth spurt. One disadvantage of the Sanders method is that most the hand stages occur after PHV has been reached, therefore making it difficult to predict how much time children have until they reach PHV, the time of maximal curve progression in scoliosis.

In addition to the hand atlases, there are multiple widely-used systems for other ossification centers in the body. Perhaps the most widely used skeletal maturity system after the Greulich and Pyle hand atlas, the Risser system uses the iliac apophysis to predict remaining vertebral growth.[18] Due to the availability of pelvic radiographs in scoliosis patients, the RIsser system remains commonly used. However, the maturation of the iliac apophysis begins after PHV, preventing the prediction of maturity before PHV. Moreover, the Risser system has been shown to poorly correlate with scoliosis curve acceleration, preventing an accurate prognosis of curve progression.[19-24] Another method to utilize the ossification of the hip is the Oxford method which grades nine ossification centers that surround the hip and has been used for evaluation slipped capital femoral epiphysis (SCFE).[25] Researches have found a narrow window of bone age, as determined by the Oxford method, where SCFE occurs.[26] Others have shown that the modified Oxford method, which consists of five ossification centers, are strongly predictive of contralateral SCFE.[27,28]

A maturation system exists that uses radiographic imaging of the foot and ankle. It was created by Hoerr, Pyle and Francis. Like its predecessor atlases of the hand and knee, the atlas made use of osseous landmarks as bone age indicators.[2-4] A recent evaluation of the Hoerr atlas found a strong correlation between estimated “bone age” and chronological age.[29] However, it is widely known that individuals of the same chronological age can differ in their skeletal age, yielding a wide spectrum of peak height velocity (PHV). This necessitates a more thorough system of skeletal maturity where PHV is incorporated and can therefore act as a surrogate measure. Such a system would be invaluable in determining the timing of surgical interventions.

For example, in determining treatment options for hallux valgus, hemiepiphysiodesis requires the patient to be skeletally immature, and osteotomies are typically performed after the patient is skeletally mature. If a maturity system could determine the amount of time before and after PHV is reached, it would be helpful in evaluating the timing of epiphysiodesis.[30-32] Greene et al. established normative values on growth of the first metatarsal but did not correlate their findings to PHV.[30] A six-stage system of calcaneal apophyseal ossification, as previously described, allows for the identification of the period of growth before and after PHV and is highly reliable, but requires lateral views of the foot.[33]

The Shorthand Bone Age (SBA) developed by Heyworth and colleagues is derived from the commonly used Greulich and Pyle method.[34] Another method worth mentioning is the Sauvegrain Method, which uses elbox x-rays. It has been shown to reliably correlate with the timing of the PHV.[35] Our group also recently developed a system utilizing the calcaneal apophysis that resembles the Risser system. This system is able to predict the skeletal maturity of children before and after PHV has been reached.[33] In our study, given that a standard AP view is routinely used for evaluating the severity of foot pathologies, we wanted to explore the utility of the phalanges of the foot for assessing skeletal maturity. To avoid additional radiation exposure, our purpose was to generate a skeletal maturity system using existing radiographic images of foot pathologies and utilize the phalanges of the foot as a surrogate for peak height velocity, which is a useful marker in timing of surgical correction in foot pathologies. We also compare our system to the calcaneal system and explore the utilization for a combined skeletal maturity system.

Materials and Methods

The children in this study are the same as those used for the Greulich and Pyle atlas of the hand and the calcaneal apophyseal ossification system, in which serial AP and lateral foot radiographs of 94 children (49 females, 45 males) were followed for over a decade with consecutive radiographs, made at least yearly from age ten to fifteen, which is the age range most associated with PHV. These radiographs were part of the Bolton-Brush collection in Cleveland, Ohio, collected by Dr. T. Wingate Todd from 1929 to 1942. These children were part of a prospective, longitudinal study of growth in healthy children, some of whom entered the study in infancy, and many of whom were followed to the end of growth. They had serial x-rays taken of their skull and left shoulder, elbow, wrist and hand, hip, knee and foot on multiple occasions. In addition, other anthropometric data were gathered whenever the children received x-rays such as height and weight. Heights were measured using a stadiometer with standardized measurement technique allowing consistency in measurements over time and between observers.

The Brush Inquiry consists of 4435 children recruited primarily through the Cleveland area schools and through referral from family physicians. The families were above average in economic and educational status. The majority of the children were white (92.2%) and the remainder were mostly black (7.7%).[3,5-6] Those who were selected for the study had no gross physical or mental defects, along with the permission of their parents to participate until the conclusion of the study.

We had 732 AP and 738 lateral x-rays available. We evaluated all AP x-rays that clearly demonstrated all of the epiphyses of the proximal phalanges of the 2nd through the 5th toes and the distal phalanx of the 1st toe and had a matching lateral x-ray taken the same day that demonstrated the entire calcaneal apophysis. This resulted in 728 matching sets of x-rays.

Using the AP view, we examined the degree of ossification and fusion of the digital proximal epiphyses of the proximal phalanges and the distal phalanx of the first ray. The lateral x-ray of the foot taken at the same session as the AP view was graded using the previously described calcaneal system.[33] All x-rays were reviewed by the author of the thesis (MRG). One hundred randomly selected sets of x-rays were evaluated by a board certified pediatric orthopedic surgeon (DRC), an orthopedic resident with considerable experience in developing and using bone maturity assessment tools (ADN), and another orthopedic resident without such experience (AMN). These three authors first graded 100 randomly selected sets of x-rays, then had a consensus building session led by MRG, then graded another 100 x-rays. Intraclass correlation coefficient (ICC) (two-way mixed model & absolute agreement) and interclass reliability coefficient were calculated using IBM SPSS and all other statistics and graphs were generated using Excel 2016 (Microsoft, Redmond, Washington).

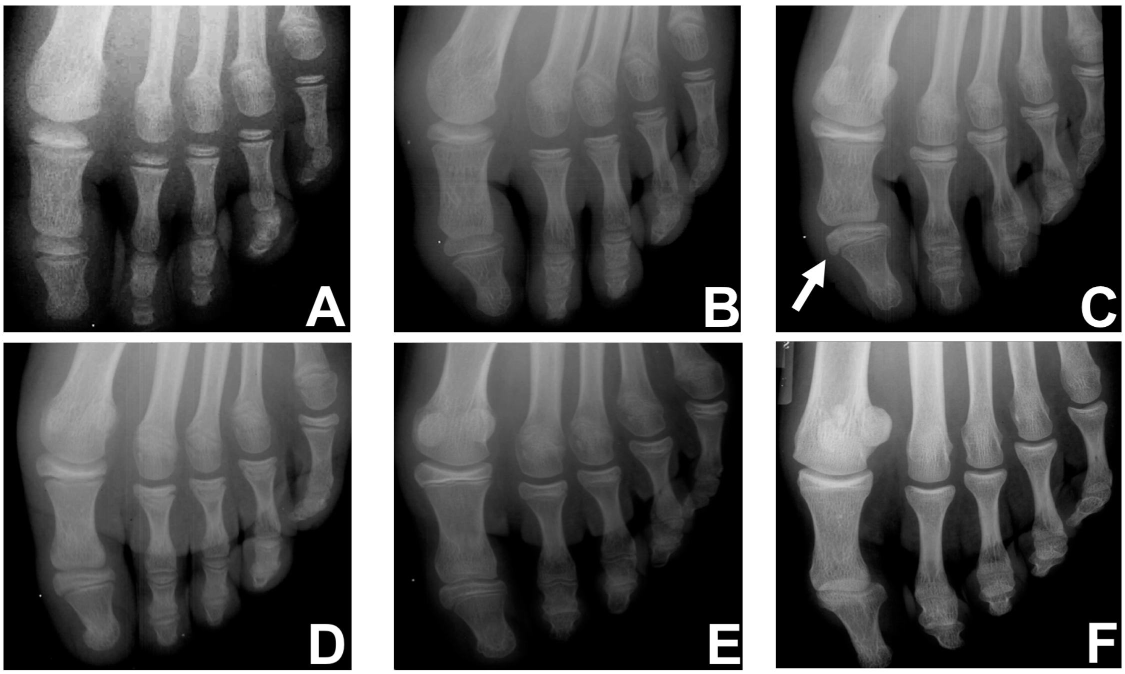
The subjects in this study had their heights taken each time x-rays were obtained. The peak height velocity was calculated using these serial height measurements after the approach of Tanner and Davies using a cubic spline to determine the maximum velocity which was defined as peak height velocity.[36] The subject's age for this value was used for the point in time of peak height velocity. Under the mentorship of Dr. Cooperman and guidance of the co-authors, the lead author graded the images, calculated statistics and wrote the published article. This work has been published in Journal of Children's Orthopaedics.[38]

Results

The ossification of the proximal phalanges and the distal phalanx of the great toe occurs in an orderly sequence. The ossification center of the distal epiphysis of the great toe is first seen at 14 and 18 months of age for females and males, respectively. By 18 and 24 months, the ossification centers of all phalanges in females and males can be seen.[2]

The orderly ossification and fusion of the foot phalanxes was divided into six stages, shown in Figure 1A-F. In MEKKA 0, at least one of the proximal phalanx has an epiphysis that is not as wide as its corresponding metaphysis. This finding is often most noticeable for the fifth proximal phalanx. MEKKA 1 is characterized by all digital proximal epiphyses of the proximal phalanges being as wide or wider than the metaphysis, or “covered,” as is the proximal epiphysis of the distal phalanx of the first digit. The epiphyseal plates of proximal phalanges 2-5 are concave in shape. MEKKA 2 is marked by the formation of a small, medial epiphyseal “hook” over the metaphysis of the distal phalanx of the first ray. Presence of the “hook” is diagnostic of stage 2, even if other criteria of stages 0 and 1 are not met. MEKKA 3 is marked by the initiation of fusion of the proximal epiphysis of the second, third, and/or fourth proximal phalanges. Fusion typically starts in the center of the physis. It is still possible to see the epiphyseal “hook” on the first ray. In MEKKA 4, fusion of the proximal epiphysis of the first and/or fifth proximal phalanges is seen. Again, it is still possible to see the epiphyseal “hook” on the first digit. In MEKKA 5, fusion of the digital proximal epiphysis and the proximal epiphysis of the distal phalanx of the first digit are complete. The complete ossification of the growth plate is represented by cortical continuity with or without the presence of a residual white physeal scar.

Figure 1. The Metaphysis, Epiphysis hooK sKeletal Assessment (MEKKA) of the phalanges



Reprinted with permission from Garcia MR, Nicholson AD, Nduaguba AM, Sanders JO, Liu RW and Cooperman DR. Ossification of the phalanges of the foot and its relationship to peak height velocity and the calcaneal system. Journal of Children's Orthopaedics 2018; 12:84-90.[38]

A) MEKKA 0: not all digital epiphyses of the proximal phalanges are covered

B) MEKKA 1: all digital epiphyses of the proximal phalanges and the proximal epiphysis of the distal phalanx of the first digit are covered. It is 'covered' when the epiphysis is as wide or wider than the metaphysis. It can also be noted that the epiphyseal plate of the proximal phalanges 2 to 5 are concave

C) MEKKA 2: capping of the metaphysis of the first digit by the epiphysis as represented by a small, medial epiphyseal ‘hook’ over the metaphysis

D) MEKKA 3: initiation of fusion of the proximal epiphyses of the second, third and/or fourth proximal phalanges. The ‘hook’ on the first ray may still be visible.

E) MEKKA 4: initiation of fusion of the proximal epiphyses of the first and/or fifth proximal phalanges. Again, the ‘hook’ on the first digit may still be visible.

F) MEKKA 5: complete ossification of all digital epiphyses of the proximal phalanges and the proximal epiphysis of the distal phalanx of the first digit

Table I shows the years before the PHV and the range of ages relative to PHV for each MEKKA stage. The presence of the “hook” of MEKKA 2 appears at a mean age of 1.79 years before PHV. Fusion of the proximal epiphysis of digits 2, 3, and/or 4 is initiated in MEKKA 3 at a mean age of 0.59 years before PHV, while complete fusion of all digital proximal epiphysis and the proximal epiphysis of the big toe occurs at a mean age of 3.90 years after PHV.

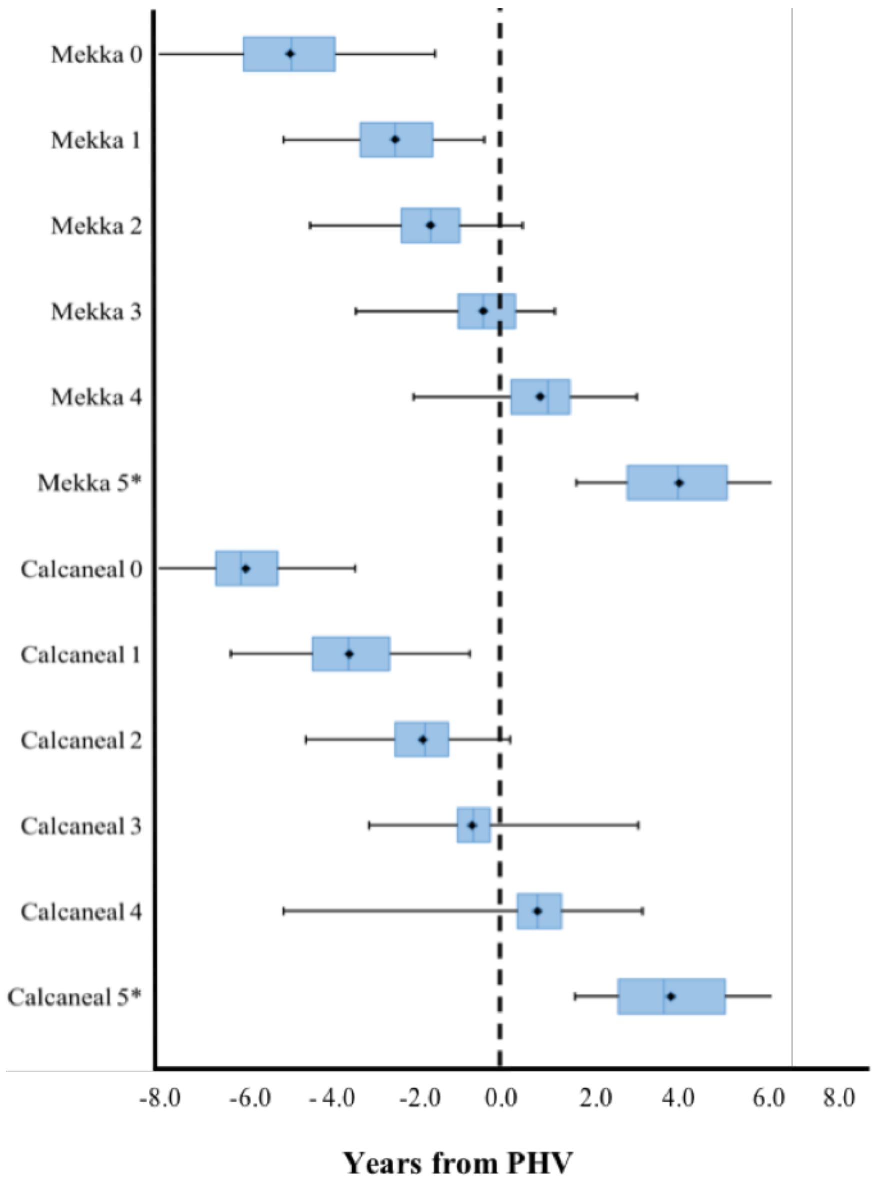
Table I Ossification of the Proximal Phalanges with Respect to Peak Height Velocity (PHV)

		Timing Relative to PHV (yr)		
Stage	No. of Samples	Mean	95% CI	Range
0	102	-5.00	-5.28 to -4.72	-8.55 to -1.69
1	67	-2.61	-2.88 bto -2.33	-5.15 to -0.57
2	87	-1.79	-2.00 to -1.58	-4.55 to 0.31
3	79	-0.59	-0.79 to -0.40	-3.50 to 1.05
4	179	0.72	0.57 to 0.86	-2.18 to 2.93
5*	35	3.90	3.43 to 4.36	1.55 to 6.89

*First appearance of stage 5. There were 179 Mekka stage 5 radiographs that were made after the first appearance of stage 5 and were not used for calculations of the first appearance of stage 5.

Figure 2 shows a comparison of the MEKKA and calcaneal system with respect to peak height velocity (PHV). PHV is achieved in MEKKA 3 and between calcaneal stages 3 and 4. There was an overlap in the initiation of fusion between the two stages (a total of 33 children that is both MEKKA 3 and calcaneal stage 4). The timing of the MEKKA stages with respect to the PHV between sexes are not statistically different as seen in Table II. The chronological age for each MEKKA stage is shown in Table III.

Figure 2. Comparison of the MEKKA and calcaneal system with respect to peak height velocity (PHV).



Reprinted with permission from Garcia MR, Nicholson AD, Nduaguba AM, Sanders JO, Liu RW and Cooperman DR. Ossification of the phalanges of the foot and its relationship to peak height velocity and the calcaneal system. Journal of Children's Orthopaedics 2018; 12:84-90.[38]

A box-and-whisker plot shows the age with respect to the PHV for the MEKKA and calcaneal stages. The black lines represent the range for each stage, while the blue box represents the middle 50% of the data. The blue line inside each box represents the median, while the black diamond in the middle represents the mean. Negative numbers represent years before PHV and positive numbers represent years after. Both MEKKA and calcaneal 5* represent the first appearance of complete fusion.

Table II Ossification of the Proximal Phalanges with Respect to PHV by Sex

		Timing Relative to PHV (yr)		
Stage	No. of Samples	Mean	95% CI	Range
Female subjects				
0	56	-5.18	-5.52 to -4.84	-7.57 to -2.23
1	40	-2.82	-3.18 to -2.46	-5.15 to -0.61
2	48	-1.79	-2.06 to -1.51	-3.78 to 0.04
3	39	-0.51	-0.78 to -0.23	-1.99 to 1.05
4	88	0.71	0.50 to 0.93	-2.18 to 2.93
5*	26	4.10	3.53 to 4.67	1.55 to 6.89
Male subjects				
0	46	-4.78	-5.25 to -4.31	-8.55 to -1.69
1	27	-2.29	-2.71 to -1.87	-4.66 to -0.57
2	39	-1.80	-2.12 to -1.48	-4.55 to 0.31
3	41	-0.67	-0.96 to -0.39	-3.50 to 0.96
4	92	0.72	0.52 to 0.92	-1.76 to 2.43
5*	9	3.32	2.66 to 3.98	2.12 to 5.08

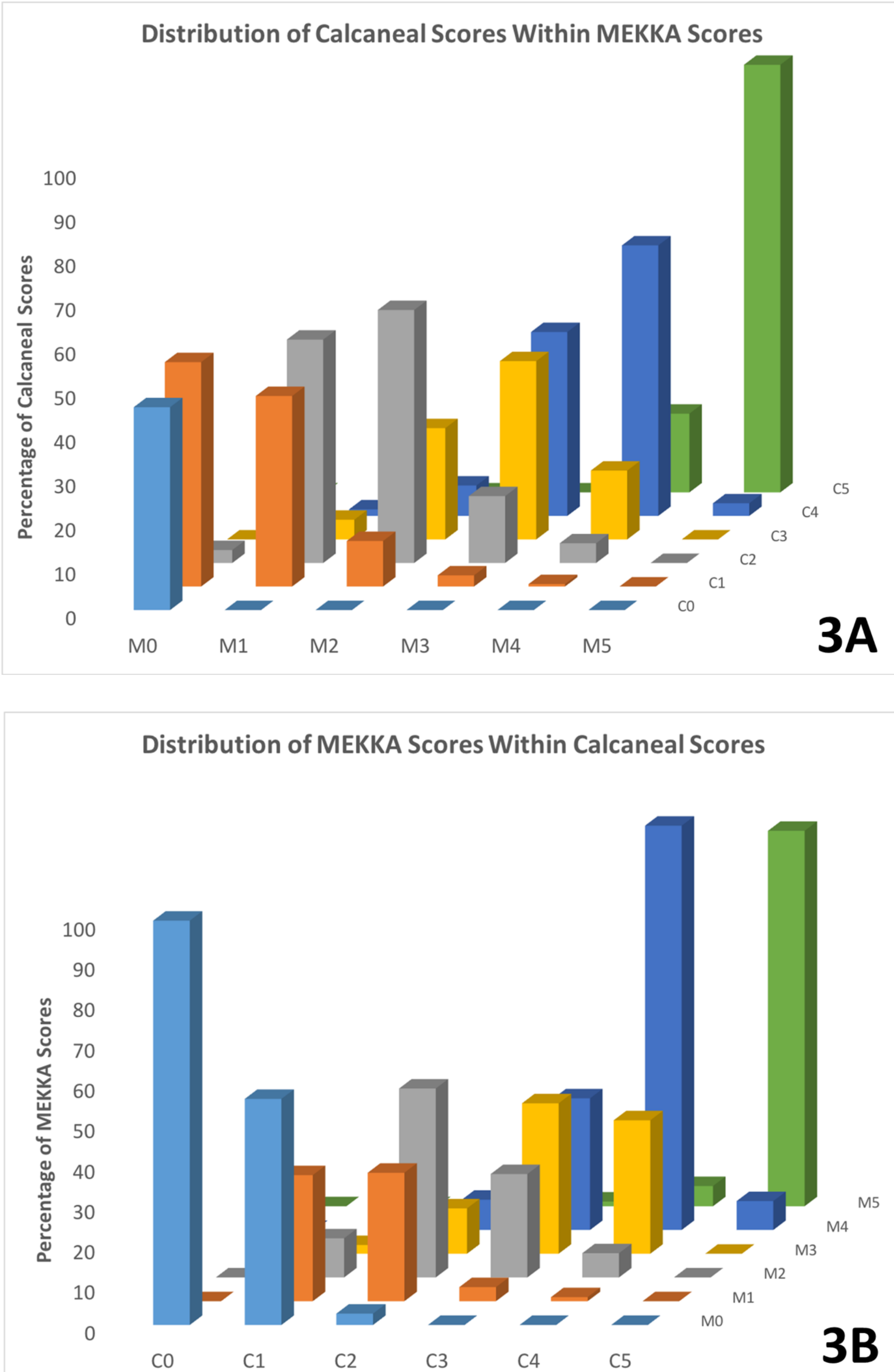
PHV = Peak height velocity
*First appearance of stage 5.

Table III Ossification of the Proximal Phalanges with Respect to Chronological Age by Sex				
			Age (yr)	
Stage	No. of Samples	Mean	95% CI	Range
Female subjects				
0	56	5.87	5.46 to 6.28	3.10 to 10.0
1	40	8.28	7.8 to 8.76	5.96 to 12.0
2	48	9.55	9.24 to 9.86	7.78 to 12.3
3	39	10.8	10.5 to 11.1	9.0 to 13.0
4	88	12.1	11.8 to 12.3	9.0 to 15.2
5*	26	15.2	14.6 to 15.8	11.9 to 18.0
Male subjects				
0	46	8.24	7.74 to 8.74	3.78 to 12.01
1	27	10.9	10.5 to 11.3	8.01 to 13.01
2	39	11.7	11.3 to 12.0	9.62 to 14.0
3	41	12.6	12.2 to 12.9	9.15 to 14.1
4	92	13.9	13.7 to 14.1	10.9 to 17.0
5*	9	16.5	15.76 to 17.24	15.0 to 18.1
*First appearance of stage 5.				

The trend, in general, between the mean and median and first and third quartile, seems to overlap which suggests a normal distribution of the data. There is a distribution of MEKKA stages corresponding to specific calcaneal scores and vice versa as shown in Figure 3. The MEKKA and calcaneal stages were combined and for each combined stage with a sample size >5, the mean number of years before or after PHV were plotted (Table IV and Figure 4).

An Intraclass correlation coefficient (ICC) range of 0.957-0.985 with an average of 0.975 and interclass reliability coefficient of 0.993 were calculated.

Figure 3. Distribution of calcaneal scores within MEKKA scores (A) and vice versa (B).

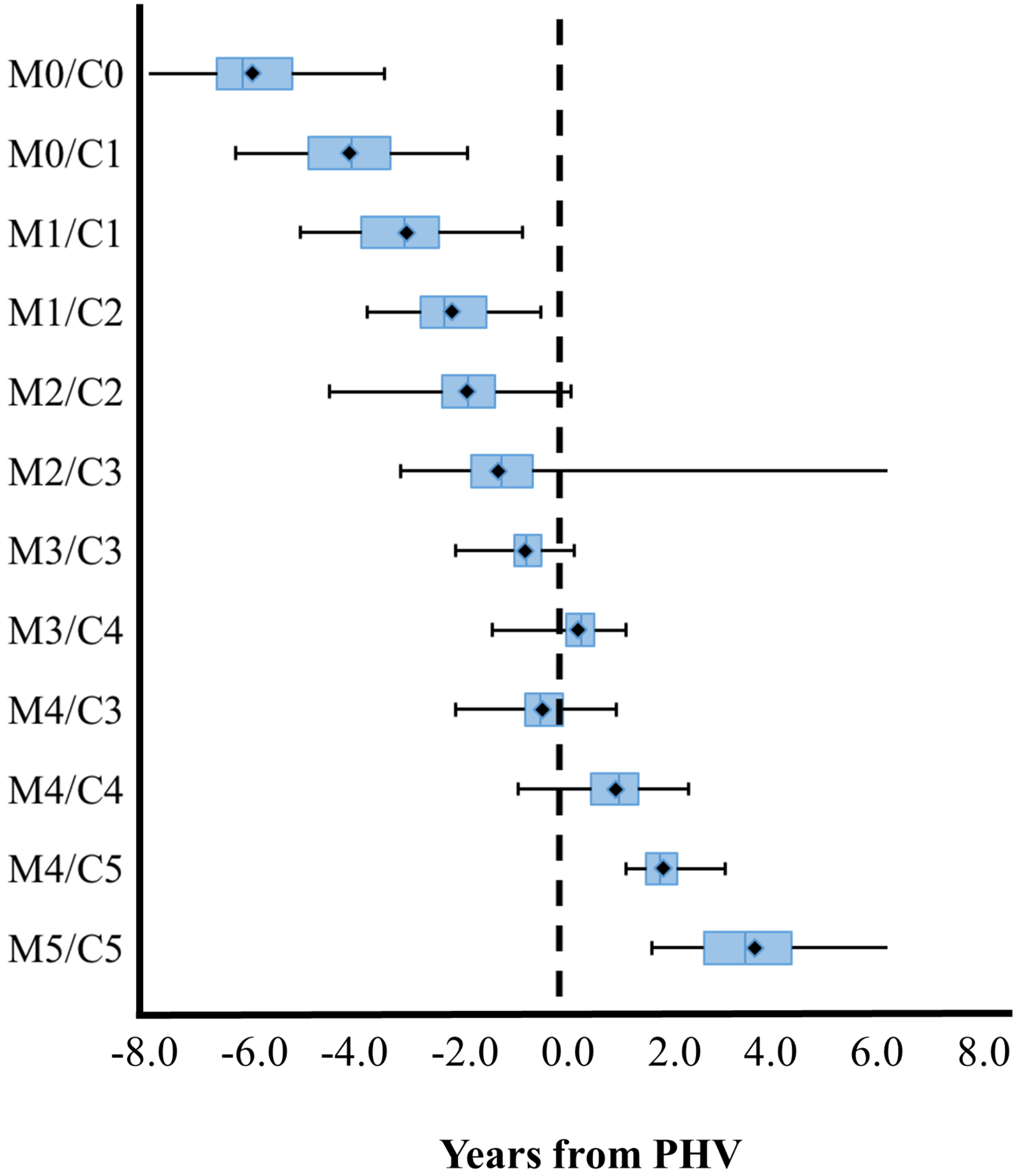


Reprinted with permission from Garcia MR, Nicholson AD, Nduaguba AM, Sanders JO, Liu RW and Cooperman DR. Ossification of the phalanges of the foot and its relationship to peak height velocity and the calcaneal system. Journal of Children's Orthopaedics 2018; 12:84-90.[38]

Table IV Combined Mekka/calcaneal stage: Years from peak height velocity (PHV)					
		Timing relative to PHV (yrs)			
Stage	n	Mean	SD	95% confidence interval	Range
M0/C0	47	-6.0	1.1	-6.3 to -5.7	-8.5 to -3.5
M0/C1	52	-4.2	1.1	-4.5 to -3.9	-6.3 to -1.9
M0/C2*	3	-3.2	1.5	-4.8 to -1.5	-4.6 to -1.7
M1/C1	29	-3.1	1.1	-3.5 to -2.7	-5.1 to -0.9
M1/C2	34	-2.2	0.9	-2.5 to -1.9	-3.8 to -0.6
M1/C3*	3	-1.1	0.6	-1.82 to -0.5	-1.8 to -0.6
M1/C4*	1	-2.2	-	-	-
M2/C1*	9	-2.8	0.5	-3.1 to -2.4	-3.6 to -1.8
M2/C2	50	-2.0	0.9	-2.2 to -1.7	-4.6 to 0.0
M2/C3	22	-1.4	0.8	-1.7 to -1.0	-3.2 to 0.0
M2/C4*	6	-0.4	0.7	-1.0 to 0.1	-1.8 to 0.3
M3/C2*	12	-1.5	0.4	-1.7 to -1.3	-1.9 to -0.6
M3/C3	32	-0.8	0.6	-1.0 to -0.6	-2.2 to 0.1
M3/C4	33	0.1	0.6	-0.1 to 0.3	-1.5 to 1.1
M4/C1*	1	-1.8	-	-	-
M4/C2*	8	-0.9	0.3	-1.1 to -0.6	-1.2 to -0.4
M4/C3	28	-0.5	0.6	-0.8 to -0.3	-2.2 to 0.9
M4/C4	110	0.9	0.7	0.7 to 1.0	-1.0 to 2.2
M4/C5	32	1.8	0.4	1.6 to 1.9	1.1 to 2.9
M5/C3*	1	3.0	-	-	-
M5/C4*	5	2.2	0.7	1.6 to 2.8	1.5 to 3.0
M5/C5	206	3.5	1.1	3.3 to 3.7	1.6 to 7.0

*Combined stages had a sample size under 20 and were excluded from Figure 4. "M" and "C" followed by the stage number represents the Mekka and calcaneal stages, respectively. 4 samples did not have a calcaneal stage and were excluded from Table IV.

Figure 4. A box-and-whisker plot of the combined MEKKA and calcaneal stages with respect to peak height velocity (PHV).



Reprinted with permission from Garcia MR, Nicholson AD, Nduaguba AM, Sanders JO, Liu RW and Cooperman DR. Ossification of the phalanges of the foot and its relationship to peak height velocity and the calcaneal system. Journal of Children's Orthopaedics 2018; 12:84-90.[38]

A box-and-whisker plot of the combined metaphysis, epiphysis hook skeletal assessment (MEKKA) (‘M’) and calcaneal (‘C’) stages show the years before (negative) and after (positive) the peak height velocity (PHV). The black lines represent the range for each stage, while the blue box represents the middle 50% of the data. The line inside each box represents the median, while the black diamond in the middle represents the mean. M0/C0 represents the immaturity up to 8+ years before PHV while M5/C5 represents full maturity of up to 8+ years after PHV. Combined stages with sample size of <20 were excluded from the graph but are shown in Table 4.

Discussion

Many methods for assessment of skeletal maturity have been developed. The most common system in use today remains the hand-wrist skeletal ages of Greulich and Pyle.[3] The atlas established a series of reference hand radiographs that can be used to establish bone age through comparison to the reference radiographs. However, it has been shown to yield a large inter-observer error and has been problematic when applied to different ethnic groups.[34-35] Moreover, this work was done prior to the understanding of PHV delineated by Tanner, and height velocity was not considered.[36-37]

An atlas of skeletal development of the foot was developed by Hoerr et al. using the same Bolton-Brush study cohort as Greulich and Pyle.[3] Both atlases were created before the concept of PHV was described by Tanner.[14-15] The Hoerr atlas established standard plates outlining the timing of appearance and patterns of ossification centers of the foot. Hoerr et al. described the proximal phalanges of the second, third, and fourth digits as the first to fuse, similar to the findings in our study. Moreover, they found that the calcaneal apophysis is the last ossification center to appear and the last to fuse, although they don’t comment on the process of calcaneal ossification.[2] Hoerr et al. found the epiphyseal-diaphyseal fusion to be complete by age 17.5 years in males and 15.0 years in females. Similarly, our data showed a mean age of 16.5 years in males and 15.2 years in females for complete fusion. We also showed that regardless of sex, ossification of the proximal phalanges and distal phalanx of the great toe, with respect to PHV, does not differ significantly. The consistency of the MEKKA ossification method makes it a suitable system for assessing PHV and skeletal maturity of the foot. For example, MEKKA 3 occurs 0.59 years (3.50 to 1.05) before PHV while actively fusing MEKKA 4 typically occurs after PHV. The relationship of a child to PHV is crucial in orthopaedic interventions that depend on skeletal maturity of the patients, such as epiphysiodesis for leg length discrepancy, posterior spinal fusion for adolescent idiopathic scoliosis, and even prophylactic pinning of the contralateral hip for a child with slipped capital femoral epiphysis (SCFE).[13-14,39-42]

The MEKKA system also provides a valuable tool in the treatment and management of foot pathologies such as juvenile hallux valgus. Hemiepiphysiodesis of the great toe metatarsal is a treatment for juvenile hallux valgus,[30-31] however, this procedure requires an open epiphysis with growth potential that can be translated into angular correction of the deformity. It could also be used in predicting the amount of growth remaining when a patient presents with a Salter-Harris Type IV fracture of a physis in the foot (phalangeal or metatarsal), determining whether to treat surgically or conservatively. The MEKKA system acts as a complimentary system to the calcaneal system, increasing the accuracy of predicted growth and PHV identification, facilitating the timing of surgery. Additionally, information about growth potential could be gathered retrospectively from previous hemiepiphysiodesis surgeries to judge the appropriateness of the timing of these surgical interventions.

Many attempts have been made to simplify the radiographic assessment of skeletal age in pediatric and adolescent patients. The Sanders method[7], derived from the Tanner-Whitehouse-III and Greulich and Pyle systems, uses ossification of the phalanxes of the hand and wrist radiographs to define the skeletal maturity stage, which is then correlated with a predictive model of scoliosis curve progression.[22] The Shorthand Bone Age (SBA) method of Heyworth uses a single radiographic criterion from the Greulich and Pyle atlas for females between ages of 10 to 16 years and males 12.5 to 16 years.[43] Another method worth mentioning is the Sauvegrain Method, a 27-point scoring system of the elbow, which has been shown to reliably correlate with the timing of the PHV.[15]

The Risser system is one of the most commonly used skeletal maturity systems, due to the visibility of the iliac apophysis excursion on PA views of the spine and correlation with end of spinal growth.[44] Similarly, the calcaneal system uses extension of the calcaneal apophysis to determine maturity. In contrast to the Risser system which primarily occurs after PHV, the calcaneal system has ossification stages occurring both before and after PHV, allowing localization of PHV.[33] Moreover, the MEKKA system can assess maturity of the foot from an AP foot radiograph, whereas the calcaneal system requires a lateral foot radiograph. Neither the MEKKA nor the calcaneal systems requires gonadal exposure to radiation. If AP and lateral foot radiographs are both obtained for a patient, they can have their calcaneal and MEKKA stages both determined for more precise determination of maturity relative to PHV.

Imaging becomes a limiting factor for the MEKKA staging system, as appreciation of the physis requires a radiograph to be taken nearly perpendicular to the physeal plate. This burden can be reduced if the indication for imaging is communicated. A specific limitation of the study is the age of the Bolton-Brush collection, as the radiographs are from 80 years ago. There is evidence that children are reaching puberty at earlier ages today.[45] However, our study uses PHV rather than chronological age which compensates for the earlier puberty onset of children today. Other concerns include lack of data from children with varying ethnic backgrounds, since the vast majority of patients in the Bolton-Brush study came from upper middle class, white families from the Cleveland area.[6]

In conclusion, our study described the ossification pattern of the phalanxes of the foot, creating a system where an anteroposterior (AP) foot radiograph can be used to determine skeletal maturity relative to skeletal age and PHV. Our system was compared to the calcaneal apophysis system, and if an AP and lateral foot x-rays are both taken, the MEKKA and calcaneal systems can be combined to judge the maturity closely. This system will allow orthopaedic surgeons to determine the timing of surgical intervention for foot deformities, such as hallux valgus, and could potentially shed light on the natural history of progression of clubfoot and pes cavus in maturing adolescents.

References

1. Kumar S. Tall stature in children: differential diagnosis and management. *Int J Pediatr Endocrinol.* 2013(Suppl 1):P53.
2. Hoerr NL, Pyle S, Francis C. Radiographic atlas of skeletal development of the foot and ankle: a standard reference. Springfield, IL: Charles C. Thomas Publisher; 1962.
3. Greulich WW, Pyle SI. Radiographic atlas of the skeletal development of the hand and wrist. *Am J Med Sci.* 1959;238-393.
4. Pyle SI and Hoerr NL. Radiographic atlas of the skeletal development of the knee: a standard reference. Springfield, IL: Charles C Thomas Publisher; 1955.
5. Todd TW. Atlas of skeletal maturation (hand). St. Louis: C.V. Mosby; 1937.
6. Nelson S, Hans MG, Broadbent BH, et al. The Brush inquiry: an opportunity to investigate health outcomes in a well-characterized cohort. *Am J Hum Biol.* 2000 Jan;12(1):1-9.
7. Sanders JO, Khoury JG, Kishan S, et al. Predicting Scoliosis Progression from Skeletal Maturity: A Simplified Classification During Adolescence. *J Bone Joint Surg Am.* 2008;90:540-53.
8. Büken B, Safak AA, Yazici B, Büken E, Mayda AS. Is the assessment of bone age by Greulich-Pyle method reliable at forensic age estimation for Turkish children? *Forensic science international.* 2007;173(2):146-53.
9. Van Rijn RR, Lequin MH, Robben SG, Hop WC, van Kuijk C. Is the Greulich and Pyle atlas still valid for Dutch Caucasian children today? *Pediatric radiology.* 2001;31(10):748-52.
10. Loder RT, Estle DT, Morrison K, Eggleston D, Fish DN, Greenfield ML, et al. Applicability of the Greulicha dn Pyle skeletal age standards to black and white children of today. *American Journal of Diseases of Children* 1993;147(12):1329-33.
11. Tanner JM, Whitehouse R, Cameron N, Marshall W, Healy M, Goldstein H. Assessment of skeletal maturity and prediction of adult height (TW2 method): Academic Press London; 1975.
12. Sanders JO, Little DG, Richards BS. Prediction of the crankshaft phenomenon by peak height velocity. *Spine.* 1997;22(12):1352-6.
13. Sanders JO. Maturity indicators in spinal deformity. *J Bone Joint Surg Am.* 2007 Feb;89(Suppl 1):14-20.
14. Sanders JO, Browne RH, McConnell SJ, et al. Maturity assessment and curve progression in girls with idiopathic scoliosis. *J Bone Joint Surg Am.* 2007 Jan;89(1)64-73.
15. Hans SD, Sanders JO, Cooperman Dr. Using the Sauvegrain method to predict peak height velocity in boys and girls. *J Pediatr Orthop.* 2008;28:836-839.
16. Marshall W, De Limongi Y. Skeletal maturity and the prediction of age at menarche. *Annals of human biology.* 1976;3(3):235-43.

17. Cox LA. Tanner-Whitehouse method of assessing skeletal maturity: problems and common errors. *Hormone research.* 1996;45 Suppl 2:53-5. Epub 1996/01/01.
18. JC R. The Iliac apophysis; an invaluable sign in the management of scoliosis. *Clinical orthopaedics.* 1957;11:111-9.
19. Noordeen M, Haddad FS, Edgar MA, et al. Spinal growth and a histologic evaluation of the Risser grade in idiopathic scoliosis. *Spine.* 1999;24(6):535-8.
20. Peterson LE, Nachemson AL. Prediction of progression of the curve in girls who have adolescent idiopathic scoliosis of moderate severity. Logistic regression analysis based on data from The Brace Study of the Scoliosis Research Society. *The Journal of Bone & Joint Surgery.* 1995;77(6):823-7.
21. Risser JC, Ferguson AB. Scoliosis: its prognosis. *The Journal of Bone & Joint Surgery.* 1936;18(3):667-70.
22. Karol LA, Johnston CE, Browne RH, et al. Progression of the curve in boys who have idiopathic scoliosis. *The Journal of Bone & Joint Surgery.* 1993;75(12):1804-10.
23. Urbaniak J, Schaefer W, Stellling FH III. Iliac apophyses: prognostic value in idiopathic scoliosis. *Clinical orthopaedics and related research.* 1976;116:80-5.
24. Little DG, Song KM, Katz D, et al. Relationshop of Peak Height Velocity to Other Maturity Indicators in Idiopathic Scoliosis in Girls*. *The Journal of Bone & Joint Surgery.* 2000;82(5):685-693.
25. Acheson R. The Oxford method of assessing skeletal maturity. *Clinical orthopaedics.* 1957;10:19.
26. Loder RT, Starnes T, Dikos G. The narrow window of bone age in children with slipped capital femoral epiphysis: a reassessment one decade later. *J Pediatr Orthop.* 2006;26(3):300-6.
27. Stasikelis PJ, Sullivan CM, Phillips WA, et al. Slipped Capital Femoral Epiphysis. Prediction of Contralateral Involvement*. *The Journal of Bone & Joint Surgery.* 1996;78(8):1149-55.
28. Popejoy D, Emara K, Birch J. Prediction of contralateral slipped capital femoral epiphysis using the modified Oxford bone age score. *J Pediatr Orthop.* 2012;32(3):290-4.
29. Hackman L, Davies CM, Black S. Age estimation using foot and radiographs from a modern Scottish population. *J Forensic Sci*. 2013 Jan;58(Suppl 1):S146-50. Epub 2012 Oct 19.
30. Greene JD, Nicholson AD, Sanders JO, et al. Analysis of Serial Radiographs of the Foot to Determine Normative Values for the Growth of the First Metatarsal to Guide Hemiepiphysiodesis for Immature Hallux Valgus. *J Pediatr Orthop.* 2015.
31. Davids JR, McBrayer D, Blackhurst DW. Juvenile hallux valgus deformity: surgical management by lateral hemiepiphysiodesis of the great toe metatarsal. *J Pediatr Orthop*. 2007;27:826-830.
32. Morrissy RT, Weinstein SL. *Lovell and Winter's Pediatric Orthopaedics,* 6th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2006.

33. Nicholson AD, Liu RW, Sanders JO, et al. Relationship of calcaneal and iliac apophyseal ossification to peak height velocity timing in children. *J Bone Joint Surg Am.* 2015;97:147-54.
34. Cundy P, Paterson D, Morris L, et al. Skeletal age estimation in leg length discrepancy. *J Pediatr Orthop.* 1988;5:513-15.
35. Mansourvar M, Ismail MA, Raj RG, et al. The applicability of Greulich and Pyle atlas to assess skeletal age for four ethnic groups. *Journal of Forensic and Legal Medicine.* 2014(22):26-29.
36. Tanner JM, Davies PS. Clinical longitudinal standards for height and height velocity for North American children. *J Pediatr.* 1985 Sep;107(3):317-29.
37. Tanner J, Healy M, Goldstein H, et al. Assessment of skeletal maturity and prediction of adult height (TW3). London: WB Saunders; 2001.
38. Garcia MR, Nicholson AD, Nduaguba AM, et al. Ossification of the phalanges of the foot and its relationship to peak height velocity and the calcaneal system. *Journal of Children's Orthopaedicss.* 2018;12:84-90
39. Song KM, Little DG. Peak height velocity as a maturity indicator for males with idiopathic scoliosis. *J Pediatr Orthop.* 2000 May-Jun;20(3):286-8.
40. Sanders JO, Browne RH, Cooney TE, et al. Correlates of the peak height velocity in girls with idiopathic scoliosis. *Spine* (Phila PA 1976). 2006 Sep 15;31(20):2289-95.
41. Hauspie R, Bielicki T, Koniarek J. Skeletal maturity at onset of the adolescent growth spurt and at peak velocity for growth in height: a threshold effect? *Ann Hum Biol.* 1991 Jan-Feb;18(1)23-9.
42. Hagg U, Taranger J. Skeletal stages of the hand and wrist as indicators of the pubertal growth spurt. *Acta Odontol Scand.* 1980;38(3):187-200.
43. Heyworth BE, Osei DA, Fabricant PD, et al. The Shorthand Bone Age Assessment: A Simpler Alternative to Current Methods. *J Pediatr Orthop.* 2013;33:569-574.
44. Risser JC. The iliac apophysis; an invaluable sign in the management of scoliosis. *Clin Orthop.* 1958;11:111-9.
45. Duval-Beaupere G, Dubousset J, Queneau P, et al. A unique theory on the course of scoliosis. *Presse Med.* 1970;78:1141-1146.