Review Article

Understanding Skeletal Growth and Predicting Limb-Length Inequality in Pediatric Patients

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Abstract

Limb-length inequality in a child can be a complex condition for patients, parents, and medical providers. Managing these patients and explaining the treatment options to families requires knowledge of the potential risks associated with leaving a discrepancy untreated and a thorough understanding of skeletal growth. The provider must also be familiar with the available growth prediction methods as treatment is influenced by the anticipated discrepancy at skeletal maturity. This article provides an overview to skeletal growth, assessing skeletal maturity and growth prediction to help providers develop an organized and thoughtful approach to treating pediatric patients with limb-length inequalities.

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The effects of long-term limb-length inequality have not been clearly delineated in the literature. Patients with limb-length discrepancies have been shown to adopt a variety of compensatory gait mechanisms. These include increased hip and knee flexion of the longer extremity, pelvic tilt toward the shorter limb, and vaulting over or circumducting the longer limb.[1-3] Song et al[4] demonstrated that patients with an average limb-length discrepancy of 1.6 ± 2.3 cm, or a 2.2% ± 4.5% difference in leg lengths, have no demonstrable difference in gait mechanics between the short and long side. However, as discrepancies increased, patients adopted compensatory patterns including vaulting and circumduction. On average, patients adopted toe-walking as a compensatory mechanism when the limb discrepancy reached 6.5 ± 2.8 cm, or a difference ≥5.5% between the short and long leg. Patients who used toe-walking performed more total work during the gait cycle than patients who maintained a plantigrade gait.[4] When limb lengths are equalized, these compensatory mechanisms resolve and patients demonstrate a more symmetric gait.[5]

In light of these known adaptations, concerns have been raised that persistent differences in leg lengths can result in chronic pain and scoliosis. However, studies regarding the association between limb-length inequality, chronic back pain, and scoliosis are small and have had inconsistent results.[3] Although multiple studies document a correlation between leg-length discrepancy, back pain, and scoliosis, causation has not been established. These studies suggest that small leg-length differences are potentially well tolerated, but that there may be a limit beyond which spine alignment and biomechanics are negatively affected and authors have yet to determine what the limit is.[3]

It has been documented that some patients with limb-length inequality have increased pain in the groin on the side of the longer limb, causing concern for arthritic changes in the hip. Sustained pelvic obliquity throughout gait can potentially result in dynamic uncovering of the femoral head with point-loading causing increased weight bearing on the articular cartilage of the hip.[5] This may be a mechanism through which hip arthrosis of the longer limb can develop. However, because less than 40% of the gait cycle is spent in single limb stance, possibility is that the altered weight transmission across the articular cartilage in patients with limb-length discrepancies may not cause lasting effects.[6] The literature citing a direct correlation between limb-length inequality and arthrosis has produced variable conclusions.[7,8]

Caring for patients with limb-length inequality requires an understanding of both skeletal growth and available prediction methods. This information, along with an understanding of the long-term effects of limb-length discrepancy on patient function and quality of life, can then be used to help determine an appropriate treatment approach.

Skeletal Growth

Children grow rapidly during the first 5 years of life. After age 5, the growth rate slows but remains steady until puberty. During the pubertal growth spurt, peak height velocity (PHV) is reached with some children increasing in height by as much as 1 cm per month.[9] In addition, two-thirds of residual growth is attributable to the growth of the lower extremities after age 5.[10]

Pubertal growth occurs in two phases. PHV is the first phase and corresponds with a bone age of 13 to 15 in males and 11 to 13 in females.[9,10] During the second stage of pubertal growth, adolescents become more skeletally mature and the rate of growth slows until full skeletal maturity is achieved. This transition coincides with menarche in females.[9,10] The Risser sign has been used to help predict PHV and adolescent growth in the setting of scoliosis. However, neither PHV nor the Risser sign has specifically been used to assist with skeletal maturity assessment in the setting of limb-length inequality, and the Risser classification has poor interobserver and intraobserver reliability compared with other methods of skeletal maturity assessment.[9-11]

Recently, attention has been paid to trying to determine when an adolescent achieves 90% of his or her ultimate height. Puberty has been shown to coincide with 86% ultimate height, whereas PHV coincides with 90% ultimate height.[9,12] For development of new prediction systems and optimization of current systems, 90% ultimate height represents a better benchmark than PHV because it can be easily calculated for any child with yearly measurements to maturity, whereas PHV is more difficult to pinpoint on an individual basis. Although calculating 90% ultimate height may be more predictable than determining the occurrence of PHV in a patient, the utility of this information in managing patients with limb-length discrepancies has yet to be delineated in the literature.

Early in development, lower extremity height accounts for approximately 35% of total skeletal height. However, by maturity, the lower extremities account for almost 50% of height, indicating that lower extremity growth accounts for an increasing proportion of total growth as children grow.[9] White and Stubbins[13] published that the distal femoral physis grows at a rate of 3/8 inch (9 mm) and the proximal tibial physis grows at a rate of ¼ inch (6 mm) annually. Through careful documentation of annual changes in stature, femoral length, and tibial length in children, Anderson et al showed that 71% of femoral growth and 57% of tibial growth comes from the distal femoral and proximal tibial physes, respectively, and that these physes account for about 37% and 28% of total lower extremity growth, respectively (Figure 1).[14-16] Based on these data, we can calculate approximate annual growth from each of the lower extremity physes.

Figure 1

mm/Yr	% Bone Growth	% Limb Growth
3	29% Femur	13%
9	71% Femur	37%
6	57% Tibia	28%
4	43% Tibia	22%

Radiograph showing the percentage contribution of the femoral and tibial physes to bone growth, lower limb growth, and average annual growth of each physis.

Determining Skeletal Age

Prediction of growth requires an accurate assessment of skeletal maturity. Chronologic age only corresponds to skeletal age within a 6-month range in 49% of boys and 51% of girls.[10] As many as 26% of individuals have a skeletal age that varies greater than 1 year from chronologic age.[10,17] It has been shown that, before onset of the adolescent growth spurt, chronologic age is superior to skeletal age

Figure 2

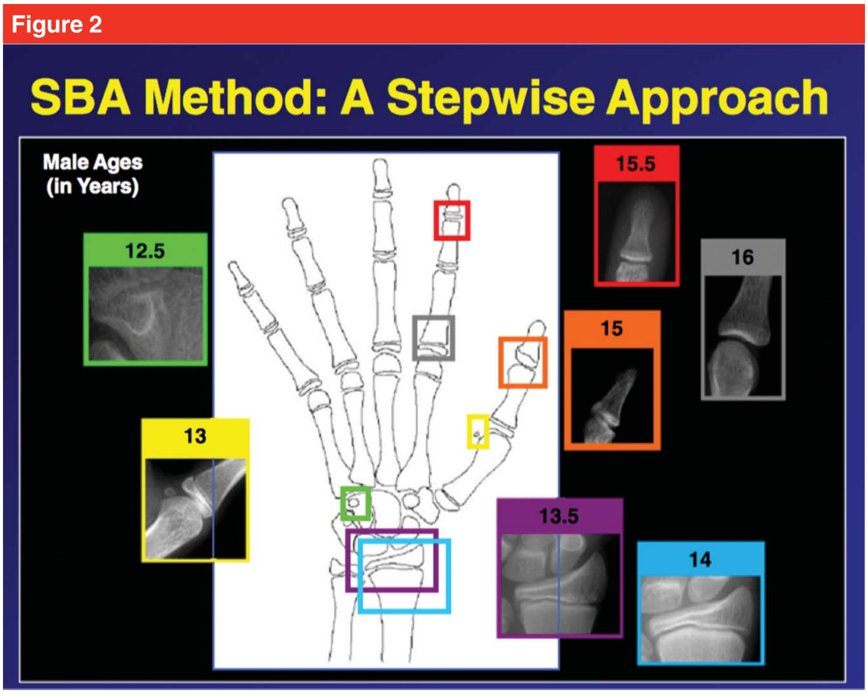

Figure showing shorthand bone age assessment for males. This figure demonstrates a characteristic change in the bone age radiograph at key time points during the male adolescent growth spurt. (Reproduced with permission from Heyworth BE, Osei DA, Fabricant PD, et al: The shorthand bone age assessment: A simpler alternative to current methods. *J Pediatr Orthop* 2013;33:569-574.)

for predicting ultimate limb length. However, skeletal age is superior for predicting limb length once the child enters his or her adolescent growth spurt.[18]

The most common tool for evaluating bone age is through use of the Greulich and Pyle atlas.[19] Although commonly used, this method requires immediate access to the atlas in the clinical setting and relies on the subjective assessment of hand radiographs. In addition, wide intervals between reference standards exist for both females and males at critical periods of pubertal growth.[19] This method also requires that patients have a normal left hand.[9] The second most common system is the Tanner Whitehouse system. By staging 20 different bones in the hand, this system offers better reliability than the Greulich and Pyle system, but takes substantially more time to perform. To help minimize variability in bone age assessment, computer software systems such as Bone Xpert have been developed. These programs analyze differences in bone age radiographs to determine skeletal age. This method has been shown to be faster and potentially introduces less variability in bone age analysis,[20] although rigorous validation studies are still lacking.

Because skeletal age has been shown to be a more accurate predictor of growth in the peri-pubertal patient, multiple methods have been described to help assess skeletal maturity in this specific age range. The shorthand Greulich and Pyle method specifically describes the key features on hand radiographs for males between ages 12.5 and 16 and females between ages 10 and 14 (Figures 2 and 3).[21] This method simplifies assessing skeletal age for adolescents in the peri-pubertal range. However, this method has not been validated against a true skeletal maturity benchmark.[21]

The Sauvegrain method uses radiographic changes seen around the elbow to determine skeletal age.[22,23] Elbow radiographs are not helpful for determining skeletal age in young children because the elbow is mainly cartilaginous and ossification centers do not display remarkable morphologic characteristics.[9] However, this method is very useful for females between ages 10 and 13 and males between ages 12 and 15 because specific morphologic changes occur around the time of puberty. The full Sauvegrain method is based on a 27-point scoring system of anatomic landmarks including the lateral condyle, trochlea, olecranon, and proximal radius.[23] The simplified Sauvegrain method uses five distinct changes that occur around the olecranon apophysis on lateral radiographs. This allows skeletal age to be determined in regular 6-month intervals in females between ages 11 and 13 and in males between ages 13 and 15. This method has been shown to have a short learning curve and is also clinically relevant because the radiographic changes are specifically seen during the adolescent growth spurt.[22] However, this method has also not been validated against a true skeletal maturity benchmark.

The Tanner Whitehouse III and the Sanders skeletal stage methods of skeletal age assessment analyze the radiographic changes seen in the epiphyses and physes of the phalanges, metacarpals, distal radius, and ulna on hand radiographs (Table 1). Skeletal maturity is described in eight stages, with stages 1 and 2 corresponding to the prepubertal growth spurt, three and four to the pubertal growth spurt, and five through eight to the eventual progression to full skeletal maturity.[24,25] This method has been used to guide the treatment of adolescent idiopathic scoliosis, but its use in managing limb-length inequality has been limited. It has been shown that Sanders stage 2 occurs immediately before both PHV and to achieving 90% ultimate height, whereas stage 3 occurs immediately after these maturity milestones. The transition from stage 2 to stage 3 correlates with 90% final height and the onset of PHV.[12]

Figure 3

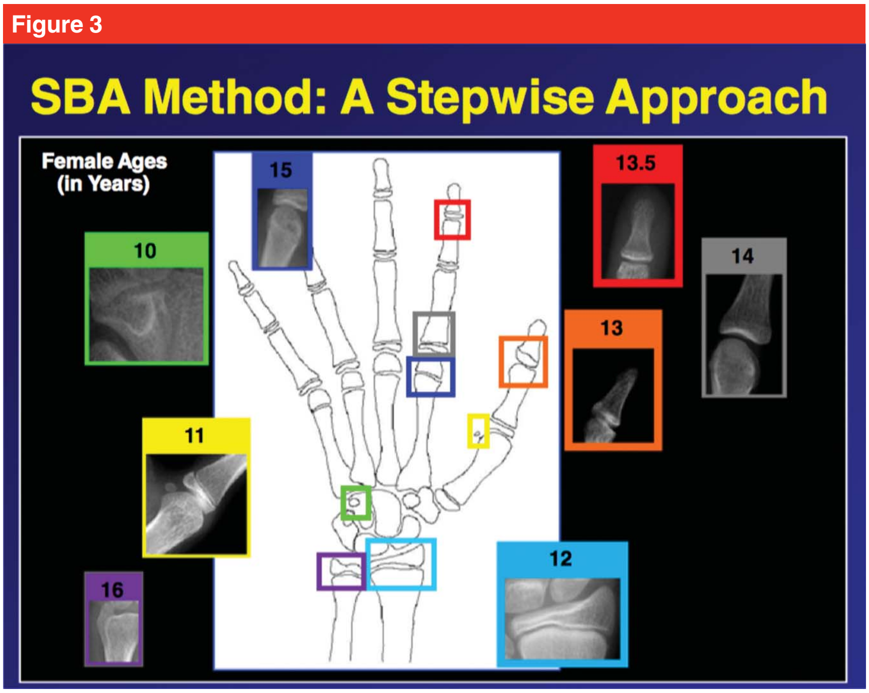

Figure showing shorthand bone age assessment for females. This figure demonstrates a characteristic change in the bone age radiograph at key time points during the female adolescent growth spurt. (Reproduced with permission from Heyworth BE, Osei DA, Fabricant PD, et al: The shorthand bone age assessment: A simpler alternative to current methods. *J Pediatr Orthop* 2013;33:569-574.)

Table 1

Skeletal Maturity Systems Focused on Peak Height Velocity

Name	Radiograph	Validation	Strengths	Limitations
Shorthand Greulich and Pyle	Left hand	Minimal	Quick, simple	Need additional clinical data to validate
Sauvegrain	Elbow	Minimal	Quick, simple	Need additional clinical data to validate
Sanders Hand	Left hand	Yes	Quick, relatively simple	Clinical data mainly on scoliosis

Growth Prediction Methods

Multiple growth prediction methods have been described (Table 2). The arithmetic method (also called the White-Menelaus method or the Menelaus[26] calculation) has been described as a rapid way to predict limb-length inequality with the benefit of not requiring access to specific radiographs or a Greulich and Pyle atlas. However, it relies on chronologic age and assumes that females stop growing at age 14 and males stop growing at age 16, with yearly growth of 0.375 inches from the distal femur and 0.25 inches from the proximal tibia annually (Figure 1). According to this method, a 12-year-old female who developed a complete distal femoral physeal arrest after a trauma would be expected to have an ultimate limb-length difference of 1.8 cm at skeletal maturity, whereas a 12-year-old male with the same injury and physeal arrest would be expected to have an ultimate discrepancy of 3.6 cm. If these patients were markedly more or less skeletally mature than their chronologic ages, these calculations may not be accurate.

Green and Anderson had multiple publications that have contributed to our understanding of skeletal growth and growth prediction. In 1963, the authors published charts including changes in stature, femoral length, and tibial length from data obtained from 100 children, 51 of whom were healthy and 49 who had a history of unilateral poliomyelitis, with ages between 8 and 18.[14] One year later, Anderson et al created growth-remaining charts based on measurements of serial radiographs of 134 otherwise healthy boys and girls from age one through skeletal maturity.[16] Their growth-remaining charts have been widely used to help predict limb-length inequality at maturity and plan the timing of epiphysiodesis. However, the information for these graphs is based on data gathered from select groups of patients, which make it unclear whether they are truly applicable to a wide range of patients with regional,

Table 2

Growth Prediction Methods

Name	Requirements	Strengths	Limitations
Arithmetic	Age, sex, discrepancy data	Quick, simple	Assumed yearly growth, does not incorporate skeletal age
Green and Anderson	Age, sex, discrepancy data	Simple	Developed on homogenous group
Moseley	Age, sex, skeletal age, and discrepancy data from three visits	Good validation studies	Time consuming, requires multiple data points
Multiplier	Age, sex, discrepancy data	Quick, simple	Recent study suggests that this may be least accurate[17] (accuracy improves if skeletal rather than chronologic age is used for calculation)

racial, ethnic, and generational differences.

In 1977, Moseley[27] published the straight-line method. This method can be used to predict both limb-length inequality at skeletal maturity and the optimal time point for epiphysiodesis for patients diagnosed with limb-length inequality early in their skeletal growth. It can also take into account previous lengthenings and/or iatrogenic or pathologic epiphysiodeses. Unlike the Green-Anderson charts, this method takes a patient's skeletal age into account when predicting growth. The method requires having access to a minimum of three bone age and three lower extremity radiographs and/or scanograms to complete the prediction method as well as access to special graph paper and a Greulich and Pyle atlas. Consequently, this can be a time-consuming method that can make it difficult to use in a busy clinical setting.

More recently, Paley et al[28] popularized the multiplier method. These authors argue that lower limbs follow a biological growth constant based on patient age and sex. The developers use Green and Anderson's growth data to calculate age- and sex-specific coefficients that can be used to calculate the growth-remaining through skeletal maturity.[28] Because the multiplier method is based on a ratio of growth over time, it eliminates differences in growth due to ethnicity and race.[29,30] Unlike the straight-line graph, calculation of ultimate limb-length discrepancy for congenital anomalies requires only a single data point so that patients can theoretically be given an estimate of limb-length discrepancy at their first clinic visit (calculation of differences for developmental discrepancies requires knowledge of the child's limb lengths at two different time points). The creation of multiple smartphone applications can make it easier for clinicians to rapidly calculate limb-length inequality at maturity and determine an age at which an epiphysiodesis should be performed.[31] One critique of this method is that it relies on chronologic rather than skeletal age, which can lead to less accurate predictions in peri-pubertal adolescents in whom skeletal age has been shown to be more accurate for prediction.[18]

Several authors have compared the available growth prediction methods to determine which provides the greatest accuracy. Little et al[32] reviewed the accuracy of the arithmetic method (referred to as the Menelaus calculation), Green and Anderson charts, and the Mosely straight-line graph by reviewing data from 110 patients who underwent epiphysiodesis for limb-length inequality. Each of the methods had approximately 10% to 20% risk of error, which would result in a limb-length difference greater than 2 cm at maturity, with the least accurate method being the computer-generated Mosely graph.[32] Makarov et al[17] compared the accuracy of the White-Menelaus, growth-remaining, Mosely straight-line, and multiplier methods by reviewing data from 77 patients treated for limb-length inequality at a single center. All patients had at least three preoperative scanograms and associated bone age radiographs of the left hand, with each pair of studies spaced at least 6 months apart, and patients were followed through skeletal maturity. The prediction methods were compared both using chronologic age and skeletal age to determine which method and which age (chronologic or skeletal) provided the most accurate prediction of short and long limb-length as well as leg-length difference at maturity. The authors found that skeletal rather than chronologic age markedly reduced prediction error of the ultimate short leg length for each of the aforementioned methods and markedly reduced the prediction error for total limb-length difference for the White-Menelaus and straight-line graph methods.[17] Each method was associated with a prediction error of approximately 1 cm, with the White-Menelaus method being the most

(0.7 ± 0.6 cm) and the multiplier Method being the least (1.1 ± 0.9 cm) accurate. The White-Menelaus method had markedly lower prediction error values compared with the multiplier Method in this cohort ($P < 0.0001$).[17]

Management of Limb-Length Inequality

When managing patients with limb-length inequality, understanding multiple patterns of growth is critical and these patterns have been documented in this patient population. Shapiro et al described five distinct growth patterns among patients with limb-length inequality.[33] Although many diagnoses that result in limb-length inequality follow a type 1 linear growth inhibition pattern, there are several conditions that have been shown to demonstrate multiple different patterns of growth, including hemihypertrophy, hemiatrophy, and neurofibromatosis.[33] Appropriate prediction of leg-length discrepancy at maturity requires an understanding of the cause of the discrepancy and the type(s) of growth that can be seen with the underlying condition. Most prediction tools, such as the multiplier Method and the Mosely straight-line graph, assume a type 1 pattern of growth and therefore may not be accurate in patients with other patterns of growth inhibition.[27]

The general recommendation regarding management of limb-length inequalities is that discrepancies predicted to be less than 2 cm at maturity do not require any surgical intervention, whereas those ranging from 2 to 4 cm at maturity can be managed with contralateral epiphysiodesis in the skeletally immature patient.[33,34] No study proves that a limb-length discrepancy up to 2 cm is asymptomatic. However, multiple studies have shown that otherwise healthy people without pain or limitation can have up to a 2 cm limb-length inequality found incidentally on examination. Authors use these population studies to argue that discrepancies less than 2 cm at skeletal maturity can either be observed or treated with a shoe lift.[35,36] An exception to the aforementioned recommendations would be if there were an unacceptable angular deformity in the short limb, which requires surgical management to restore appropriate mechanical alignment to the limb, or in a patient with symptomatic limb length discrepancy who desired permanent correction, as a shoe lift might not be used particularly when indoors.

Gradual lengthening is generally recommended for predicted discrepancies greater than 4 cm although no firm data exist in the literature upon which these treatment guidelines have been established. With the advent of internal lengthening devices, lengthening has been considered for smaller discrepancies, especially if a patient is predicted to have a short final height.[37] Internal lengthening devices have the advantage of reduced pin-site infections and minor complications compared with external fixation systems. However, the rate of more notable complications associated with lengthening is similar when internal and external lengthening methods are compared, which is important to discuss these risks with patients before going forward with limb-lengthening procedures.[38] Complications associated with limb-lengthening procedures can be notable and include muscle contractures, joint stiffness, and dislocation. Furthermore, the complexity of lengthening procedures results in technically demanding skills for surgeons. Therefore, the recommendation is that inexperienced surgeons start with smaller lengthenings and less complex cases to gain proficiency before attempting larger reconstructions.[39]

Management of the skeletally immature patient with a limb-length discrepancy requires regular follow-up along with careful clinical and radiographic assessment. Because there is a period of slow, steady growth between age five and the onset of puberty, patients with small discrepancies can be followed up annually until age 9, then every 6 months until skeletal maturity.[10] Each of the prediction methods has the potential for error. Therefore, to ensure accuracy with growth prediction, using more than one method is wise. Consistent predictions when more than one prediction tool is used and consistent predictions across multiple patient visits, allow the surgeon to be more confident in his/her assessment.[9] Tanner staging has also been recommended to ensure the accuracy of predictions, although the assessment may be outside the comfort zone of orthopaedic surgeons with low reliability reported in the literature.[9,40] Finally, comprehensive treatment of patients with leg length discrepancy requires the surgeon to take into account not just differences in limb length but also hip, knee, and ankle range of motion as well as joint stability if a lengthening is being considered.

Summary

Limb-length discrepancy has been shown to cause changes in gait patterns, with the greatest changes seen in those who have differences of 5.5% or greater.[4] There is inconsistent evidence that limb-length inequality has long-term effects on the biomechanics of the spine, hip, and knee joints. Correcting limb-length discrepancies has been shown to restore some normal gait parameters, but long-term studies demonstrating resolution of chronic back pain and prevention of arthritic changes in ipsilateral or contralateral hip and knee joints are missing from the literature.[5]

Appropriate treatment of skeletally immature patients with limb-length discrepancies requires an understanding of skeletal growth, the methods used to assess skeletal maturity, and the growth prediction methods available. Patients must be followed up serially and these examinations should include careful clinical assessments of limb-length inequality, joint range of motion, and joint stability. Radiographic evaluation of the lower extremities as well as radiographs to evaluate skeletal maturity, including hand and elbow skeletal-age radiographs, should be obtained. Multiple prediction tools should be used and predictions should be made over consecutive patient examinations to determine anticipated discrepancies at maturity and minimize errors with prediction. This knowledge allows the orthopaedic surgeon to provide patients and families with an understanding of the severity of the discrepancy and serves as a foundation for determining the appropriate treatment course for each patient.

References

References printed in **bold type** are those published within the past 5 years.

1. **Resende RA, Kirkwood RN, Deluzio KJ, Cabral S, Fonseca ST: Biomechanical strategies implemented to compensate for mild leg length discrepancy during gait. *Gait Posture* 2016;46:147-153.**
2. **Aiona M, Do KP, Emara K, Dorociak R, Pierce R: Gait patterns in children with limb length discrepancy. *J Pediatr Orthop* 2015; 35:280-284.**
3. **Sheha ED, Steinhaus ME, Kim HJ, Cunningham ME, Fragomen AT, Rozbruch SR: Leg-length discrepancy, functional scoliosis, and low back pain. *JBJS Rev* 2018;6:e6.**
4. Song KM, Halliday SE, Little DG: The effect of limb-length discrepancy on gait. *J Bone Joint Surg Am* 1997;79:1690-1698.
5. Bhave A, Paley D, Herzenberg JE: Improvement in gait parameters after lengthening for the treatment of limb-length discrepancy. *J Bone Joint Surg Am* 1999;81: 529-534.
6. Gage JR: *The treatment of gait problems in cerebral palsy*. London: Mac Keith: Distributed by Cambridge University Press, 2004, pp xiv, 448 p.
7. **Liu RW, Streitt JJ, Weinberg DS, Shaw JD, LeeVan E, Cooperman DR: No relationship between mild limb length discrepancy and spine, hip or knee degenerative disease in a large cadaveric collection. *Orthop Traumatol Surg Res* 2018;104: 603-607.**
8. Tallroth K, Ylikoski M, Lamminen H, Ruohonen K: Preoperative leg-length inequality and hip osteoarthrosis: A radiographic study of 100 consecutive arthroplasty patients. *Skeletal Radiol* 2005; 34:136-139.
9. **Iobst C: Growth of the musculoskeletal system, in Martus J, ed: *Orthopaedic Knowledge Update Pediatrics*, ed 5. Rosemont, IL, American Academy of Orthopaedic Surgeons, 2016, pp 59-68.**
10. Dimeglio A: Growth in pediatric orthopaedics, in Lovell WW, Winter RB, Morrissy RT, Weinstein SL, eds: *Lovell and Winter's pediatric orthopaedics*, ed 6. Philadelphia, Lippincott Williams & Wilkins, 2006, pp 35-63.
11. **Vira S, Husain Q, Jalai C, et al: The interobserver and intraobserver reliability of the Sanders classification versus the Risser stage. *J Pediatr Orthop* 2017;37: e246-e249.**
12. **Sanders JO, Qiu X, Lu X, et al: The uniform pattern of growth and skeletal maturation during the human adolescent growth spurt. *Sci Rep* 2017;7:16705.**
13. White J, Stubbins S: Growth arrest for equalizing leg lengths. *JAMA* 1944;126: 1146-1149.
14. Anderson M, Green WT, Messner MB: Growth and predictions of growth in the lower extremities. *J Bone Joint Surg Am* 1963;45-A:1-14.
15. Anderson M, Messner MB, Green WT: Distribution of lengths of the normal femur and tibia in children from one to eighteen years of age. *J Bone Joint Surg Am* 1964;46: 1197-1202.
16. Green WT, Anderson M: Experiences with epiphyseal arrest in correcting discrepancies in length of the lower extremities in infantile paralysis; a method of predicting the effect. *J Bone Joint Surg Am* 1947;29:659-675.
17. **Makarov MR, Jackson TJ, Smith CM, Jo CH, Birch JG: Timing of epiphysiodesis to correct leg-length discrepancy: A comparison of prediction methods. *J Bone Joint Surg Am* 2018;100:1217-1222.**
18. Sanders JO, Howell J, Qiu X: Comparison of the Paley method using chronological age with use of skeletal maturity for predicting mature limb length in children. *J Bone Joint Surg Am* 2011;93:1051-1056.
19. Greulich WW, Pyle SI, Todd TW: *Radiographic Atlas of Skeletal Development of the Hand and Wrist : Based on the Brush Foundation Study of Human Growth and development Initiated by T. Wingate Todd*. Stanford, Stanford University Press, 1950, pp xiii, 190 p.
20. De Sanctis V, Soliman AT, Di Maio S, Bedair S: Are the new automated methods for bone age estimation advantageous over the manual approaches? *Pediatr Endocrinol Rev* 2014;12:200-205.
21. 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.
22. Diméglio A, Charles YP, Daures JP, de Rosa V, Kaboré B: Accuracy of the Sauvegrain method in determining skeletal age during puberty. *J Bone Joint Surg Am* 2005;87:1689-1696.
23. Sauvegrain J, Nahum H, Bronstein H: Study of bone maturation of the elbow [French]. *Ann Radiol (Paris)* 1962;5: 542-550.
24. 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;90:540-553.
25. Tanner JM, Healey MJR, Goldstein H, Camerson N: *Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 Method)*, ed 3. London, Saunders, 2001.
26. Menelaus MB: Correction of leg length discrepancy by epiphysial arrest. *J Bone Joint Surg Br* 1966;48:336-339.
27. Moseley CF: A straight-line graph for leg-length discrepancies. *J Bone Joint Surg Am* 1977;59:174-179.
28. Paley D, Bhave A, Herzenberg JE, Bowen JR: Multiplier method for predicting limb-length discrepancy. *J Bone Joint Surg Am* 2000;82-A:1432-1446.
29. Aguilar JA, Paley D, Paley J, et al: Clinical validation of the multiplier method for predicting limb length at maturity, part I. *J Pediatr Orthop* 2005;25:186-191.
30. Aguilar JA, Paley D, Paley J, et al: Clinical validation of the multiplier method for predicting limb length discrepancy and outcome of epiphysiodesis, part II. *J Pediatr Orthop* 2005;25:192-196.
31. **Wagner P, Standard SC, Herzenberg JE: Evaluation of a mobile application for multiplier method growth and epiphysiodesis timing predictions. *J Pediatr Orthop* 2017;37:e188-e191.**
32. Little DG, Nigo L, Aiona MD: Deficiencies of current methods for the timing of epiphysiodesis. *J Pediatr Orthop* 1996;16: 173-179.

33. Herring JA: Limb length discrepancy, in Herring JA, *Texas Scottish Rite Hospital for Children. (eds): Tachdjian's pediatric orthopaedics: from the Texas Scottish Rite Hospital for Children*, ed 5. Philadelphia, PA, Elsevier Saunders, 2014, vol 2, pp 884-928.

34. Vitale MA, Choe JC, Sesko AM, et al: The effect of limb length discrepancy on health-related quality of life: Is the "2 cm rule" appropriate? *J Pediatr Orthop B* 2006;15: 1-5.

35. Rush WA, Steiner HA: A study of lower extremity length inequality. *Am J Roentgenol Radium Ther* 1946;56: 616-623.

36. Subotnick SI: Limb length discrepancies of the lower extremity (the short leg syndrome). *J Orthop Sports Phys Ther* 1981;3:11-16.

37. Liu RW, Rascoe A, Peng E, Copp J: The importance of considering ultimate height in the treatment of limb length discrepancy, in *Eurpean Pediatric Orthopaedic Society and Pediatric Orthopaedic Society of North America Annual Meeting*, Spain, Barcelona, 2017.

38. Black SR, Kwon MS, Cherkashin AM, Samchukov ML, Birch JG, Jo C: Lengthening in congenital femoral deficiency: A comparison of circular external fixation and a motorized intramedullary nail. *J Bone Joint Surg Am* 2015;97:1432-1440.

39. Dahl MT, Gulli B, Berg T: Complications of limb lengthening: A learning curve. *Clin Orthop Relat Res* 1994:10-18.

40. Slough JM, Hennrikus W, Chang Y: Reliability of Tanner staging performed by orthopedic sports medicine surgeons. *Med Sci Sports Exerc* 2013;45:1229-1234.