Normative Femoral and Tibial Lengths in a Modern Population of Twenty-First-Century U.S. Children

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Background: The Green-Anderson (GA) leg-length data remain the gold standard for the age-based assessment of leg lengths in children despite their methodologic weaknesses. We aimed to summarize current growth trends among a cross-sectional cohort of modern U.S. children using quantile regression methods and to compare the median femoral and tibial lengths of the modern U.S. children with those of the GA cohort.

Methods: A retrospective review of scanograms and upright slot-scanning radiographs obtained in otherwise healthy children between 2008 and 2020 was completed. A search of a radiology registry revealed 3,508 unique patients between the ages of 2 and 18 years for whom a standard-of-care scanogram or slot-scanning radiograph had been made. All patients with systemic illness, genetic conditions, or generalized diseases that may affect height were excluded. Measurements from a single leg at a single time point per subject were included, and the latest available time point was used for children who had multiple scanograms made. Quantile regression analysis was used to fit the lengths of the tibia and femur and overall leg length separately for male patients and female patients.

Results: Seven hundred patients (328 female and 372 male) met the inclusion criteria. On average, the reported 50th percentile tibial lengths from the GA study at each time point were shorter than the lengths in this study by 2.2 cm (range, 1.4 to 3.3 cm) for boys and 2 cm (range, 1.1 to 3.1 cm) for girls. The reported 50th percentile femoral lengths from the GA study at each time point were shorter than the lengths in this study by 1.8 cm (range, 1.1 to 2.5 cm) for boys and 1.7 cm (range, 0.8 to 2.3 cm) shorter for girls.

Conclusions: This study developed new growth charts for femoral and tibial lengths in a modern U.S. population of children. The new femoral and tibial lengths at nearly all time points are 1 to 3 cm longer than traditional GA data. The use of GA data for epiphysiodesis could result in underestimation of expected childhood growth.

Level of Evidence: Prognostic Level IV. See Instructions for Authors for a complete description of levels of evidence.

Green-Anderson (GA) growth-remaining charts are widely used by pediatric orthopaedic surgeons to predict leg lengths at skeletal maturity in order to time growth modulation procedures and to estimate expected leg-length discrepancies following premature physeal arrest[1-4]. However, the patients in the GA cohort were a homogeneous group mostly composed of Caucasians, many with unilateral paralytic poliomyelitis. The limited patient sample does not account for differences in ethnicity, socioeconomic status, or variable body height. Furthermore, with modern advances in nutrition, hygiene, and health, it is possible that stature and leg lengths have changed over time[5,6].

The growth-remaining charts presented by Anderson et al. show the means and standard deviations of the bone length measured from consecutive radiographs of the same patients made at the chronological ages of 1 to 18 years[3]. However, the modern methodology used by the World Health Organization (WHO) and the U.S. Centers for Disease Control and Prevention (CDC) to create a growth chart involves measuring many individuals of a variety of ages at 1 time point and then reporting the percentiles of the selected population. It is the standard methodology in anthropometry and the development of growth charts[7-9]. To the best of our knowledge, there have been no publications with regard to development of a modern growth chart for lower-extremity bone growth in English-language literature. Thus, the purpose of the present study was to apply the modern technique used to develop growth charts for stature and report growth charts for tibial and femoral lengths in a modern U.S. population of children.

Disclosure: The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (http://links.lww.com/JBJS/H403).

Materials and Methods

Study Subjects

With the approval of the institutional review board of our hospital (19-005809), we retrospectively reviewed standardized scanograms and biplanar slot-scanning imaging of lower limbs in children obtained as the standard of care between 2008 and 2020. A search of a radiology registry revealed 3,508 unique patients between the ages of 2 and 18 years for whom these radiographs had been made. Additional imaging from 2021 and 2022 was used as a validation data set. The medical records of each patient were carefully reviewed. All patients with systemic illness, syndromes, genetic conditions, endocrinologic disorders, cerebral palsy, hemiplegia, skeletal dysplasias, or generalized diseases that might have affected height were excluded. For patients with a history of unilateral lower-limb trauma, bone lesions, infection, or vascular malformation, we only

TABLE I Patient Characteristics

Characteristic	Female Patients (N = 328)	Male Patients (N = 372)	Total (N = 700)
Scan type*			
Standing slot-scanning radiographs	220 (67%)	240 (65%)	459 (66%)
Supine scanograms	108 (33%)	132 (36%)	240 (34%)
Patient residence or nationality*			
United States, Midwest	295 (90%)	337 (90.6%)	632 (90.3%)
United States, not Midwest	26 (8%)	27 (7.3%)	53 (7.6%)
Non-United States	7 (2%)	8 (2.2%)	15 (2.1%)
Racial category*			
White	264 (80%)	311 (84%)	575 (82%)
Non-White	64 (20%)	61 (16%)	125 (18%)
Age group*			
<1 year	6 (1.8%)	2 (0.5%)	8 (1.1%)
1 year	11 (3.4%)	22 (5.9%)	33 (4.7%)
2 years	20 (6.1%)	14 (3.8%)	34 (4.9%)
3 years	9 (2.7%)	17 (4.6%)	26 (3.7%)
4 years	14 (4.3%)	28 (7.5%)	42 (6.0%)
5 years	20 (6.1%)	15 (4.0%)	35 (5.0%)
6 years	13 (4.0%)	11 (3.0%)	24 (3.4%)
7 years	17 (5.2%)	16 (4.3%)	33 (4.7%)
8 years	24 (7.3%)	20 (5.4%)	44 (6.3%)
9 years	20 (6.1%)	13 (3.5%)	33 (4.7%)
10 years	25 (7.6%)	19 (5.1%)	44 (6.3%)
11 years	23 (7.0%)	28 (7.5%)	51 (7.3%)
12 years	34 (10.4%)	23 (6.2%)	57 (8.1%)
13 years	30 (9.1%)	25 (6.7%)	55 (7.9%)
14 years	13 (4.0%)	37 (9.9%)	50 (7.1%)
15 years	11 (3.4%)	16 (4.3%)	27 (3.9%)
16 years	18 (5.5%)	25 (6.7%)	43 (6.1%)
17 years	13 (4.0%)	33 (8.9%)	46 (6.6%)
18 years	7 (2.1%)	8 (2.2%)	15 (2.1%)
Height† *(cm)*	142.9 (118.8, 159.3)	149.3 (117.0, 170.4)	145.4 (117.8, 163.8)
Weight† *(kg)*	37.4 (22.5, 53.2)	41.1 (22.7, 65.9)	39.2 (22.5, 59.0)
Body mass index† *(kg/m²)*	18.1 (16.0, 21.6)	19.1 (16.7, 22.8)	18.5 (16.3, 22.3)
Laterality*			
Left	167 (50.9%)	194 (52.2%)	361 (51.6%)
Right	161 (49.1%)	178 (47.8%)	339 (48.4%)

*The values are given as the number of patients, with the percentage in parentheses. †The values are given as the median, with the interquartile range in parentheses.

considered the femoral, tibial, and leg lengths of the uninvolved side. For healthy children with both limb-length measurements available, only 1 set of limb-length measurements (either left or right) was randomly assigned to be considered in the analysis cohort. Thus, measurements from a single leg per subject from a single time point were included, and the latest available time point was used for children who underwent multiple scanograms. Patients who did not agree to participate in retrospective research were excluded from the study. We determined the patient's chronological age to 0.1 years. If there was >1 radiograph at that age, the later one was used (for example, if the same patient had radiographs at 17.1 and 17.6 years, the radiograph at 17.6 years was used).

Radiographic Technique

Imaging was performed according to standardized institutional protocols using 1 of 2 methods. Between 2013 and 2020, patients who had radiographs made to evaluate for leg-length discrepancy underwent imaging using biplanar slot-scanning imaging of the EOS System (EOS Imaging), which is a low-dose digital radiographic imaging system[10]. The patient stands relaxed with the lower limbs aligned in the center of the scanning field and the patellae facing anteriorly. Between 2008 and 2012, radiographs were made using a slit scanner protocol developed and validated at our center. Described by Pugh and Winkler[11], this is the standardized method that has been used at our center since 1970. Patients who were unable to remain still for the biplanar slot-scanning imaging between 2013 and 2020 also underwent imaging with the use of the supine slit scanner. While the patient was in a supine position, a slit-like x-ray beam moved down the length of the patient's legs. Tube motion and exposure are continuous and simultaneous. Radiology technicians go through extensive training to be certified

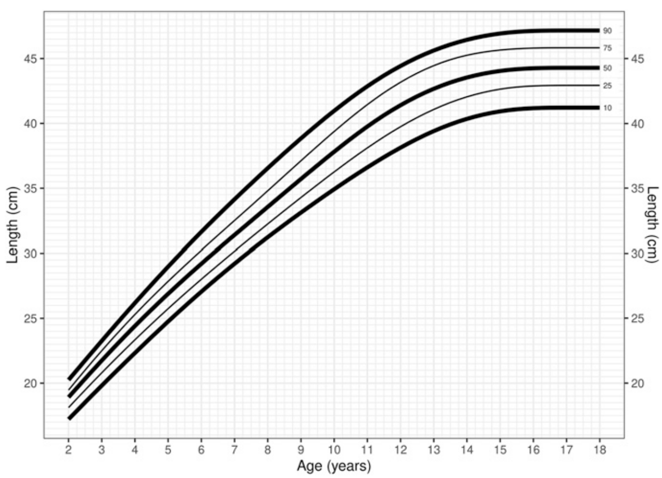

Fig. 1

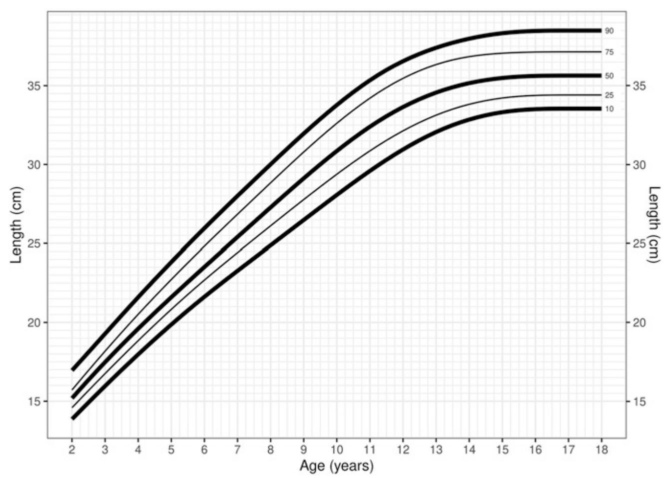

Fig. 2

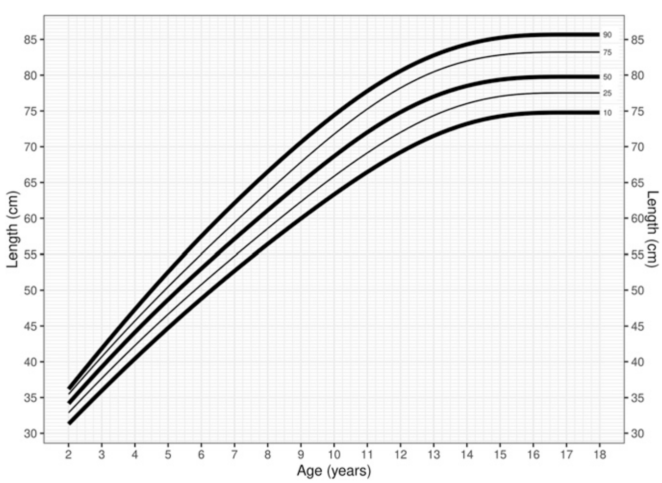

Fig. 3

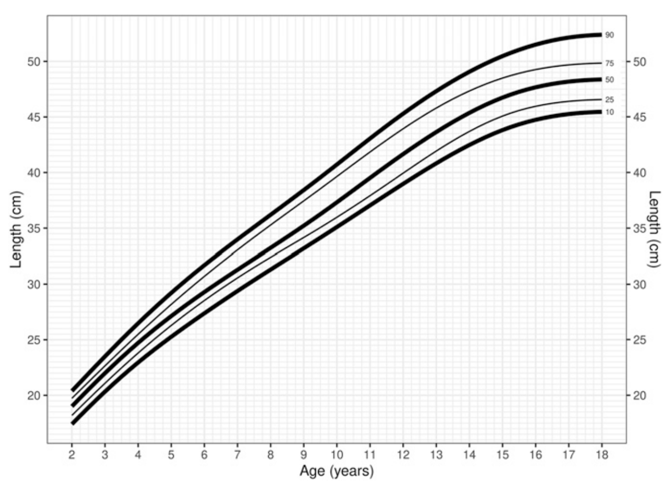

Fig. 4

Fig. 1 Female femoral length, showing 10th, 25th, 50th, 75th, and 90th percentiles (in centimeters) for the ages of 2 to 18 years. **Fig. 2** Female tibial length, showing 10th, 25th, 50th, 75th, and 90th percentiles (in centimeters) for the ages of 2 to 18 years. **Fig. 3** Female leg length, showing 10th, 25th, 50th, 75th, and 90th percentiles (in centimeters) for the ages of 2 to 18 years. **Fig. 4** Male femoral length, showing 10th, 25th, 50th, 75th, and 90th percentiles (in centimeters) for the ages of 2 to 18 years.

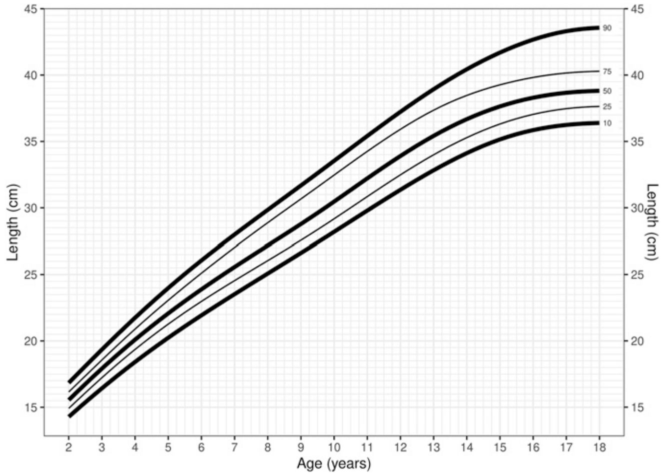

Fig. 5

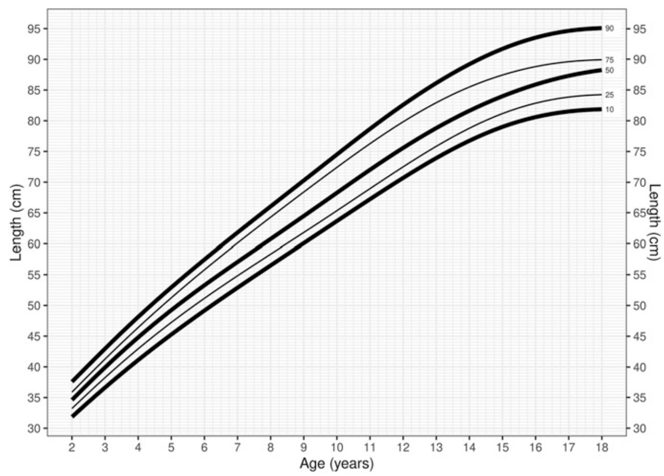

Fig. 6

Fig. 5 Male tibial length, showing 10th, 25th, 50th, 75th, and 90th percentiles (in centimeters) for the ages of 2 to 18 years. **Fig. 6** Male leg length, showing 10th, 25th, 50th, 75th, and 90th percentiles (in centimeters) for the ages of 2 to 18 years.

in scanogram measurements. Furthermore, the pediatric radiologist reviews and approves the measurements performed by the radiology technicians.

Length Measurements

Bone lengths were measured as described by Anderson and Green in 1948[4]. Measurements were made of the entire bone, including both proximal and distal epiphyses. The femoral length was measured from the proximal articulating surface of the femoral capital epiphysis to the most distal point on the lateral condyle. The tibia was measured from the midpoint of a line drawn across the proximal epiphyseal articulating surface to the midpoint of a line drawn across the distal articulating surface. We added the tibial and femoral lengths to calculate the anatomical leg length. The same radiographic landmarks were used for leg-length measurements on both types of imaging studies (standing slot scanning and supine slit scanning). Measurements were made as the standard of care by radiology technicians trained in the technique and were then reviewed and approved by a board-certified pediatric radiologist.

Statistical Analysis

Descriptive statistics were summarized for continuous and categorical data. Quantile regressions were fitted using general-purpose optimization with a penalized spline basis with 4 degrees of freedom and a smoothing parameter of $\lambda = 0.5$ at the 10th, 25th, 50th, 75th, and 90th percentiles ($\tau = 0.1$, 0.25, 0.5, 0.75, and 0.9). Bootstrap methods were implemented to calculate 95% confidence intervals (CIs) for the 10th, 50th, and 90th percentiles. Femoral, tibial, and leg length percentiles for ages of 2 to 18 years for each sex were plotted. All analyses were conducted using R version 4.1.2 (R Foundation for Statistical Computing).

Source of Funding

There was no source of funding for this study.

Results

The analysis cohort consisted of 700 subjects. Slit scanograms were made for 34% of patients and standing slot-scanning radiographs were made for 66% of patients. Most patients (90%) were from the U.S. Midwestern region. The cohort consisted of 328 female patients (47%) and 372 male patients (53%), with the race for 575 patients (82%) reported as White (Table I). The racial and ethnic distributions in our cohort are different from the demographic characteristics of the entire United States but are similar to the demographic characteristics of the U.S. Midwestern region[12].

The distribution of height (stature) and weight by age and sex generally followed trends outlined in the U.S. growth charts published by the CDC and the WHO[13,14]. Nearly equal numbers of measurements were for left (52%) and right (48%) lower limbs. The reasons for the examinations included suspected leg-length discrepancy, fracture, leg pain, idiopathic scoliosis, vascular malformation, isolated idiopathic femoral anteversion, isolated idiopathic genu varum or valgum, anterior cruciate ligament tear, sports injury, tumor, infection, or other.

Lower-Limb Growth Trends

Female and male femoral, tibial, and leg lengths at the 10th, 50th, and 90th percentiles for the ages of 2 to 18 years were summarized (Figs. 1 through 6, Tables II and III).

Comparison to GA Growth Charts

On average, compared with the current study, the reported mean 50th percentile tibial lengths from the GA cohort were 2.2 cm (range, 1.4 to 3.3 cm) shorter at each time point for boys 5 to 18 years of age and 2 cm (range, 1.1 to 3.1 cm) shorter for girls 5 to 16 years of age (Table IV). Similarly, compared with the current study, the reported mean 50th percentile femoral lengths from the GA cohort were 1.8 cm (range, 1.1 to 2.5 cm) shorter at each time point for boys 5 to 18 years of age and 1.7 cm (range, 0.8 to 2.3 cm) shorter for girls 5 to 16 years of age (Fig. 7).

TABLE II Female Femoral, Tibial, and Leg Lengths ➤

Age *(yr)*	Femoral Length* *(cm)* 10th Percentile	50th Percentile	90th Percentile
2	17.3 (16.7 to 17.9)	18.9 (18.6 to 19.2)	20.1 (19.6 to 20.9)
3	19.9 (19.3 to 20.5)	21.8 (21.5 to 22.1)	23.1 (22.7 to 23.7)
4	22.4 (21.7 to 23)	24.4 (24.1 to 24.9)	26.1 (25.6 to 26.7)
5	24.8 (23.9 to 25.4)	26.9 (26.5 to 27.4)	28.9 (28.2 to 29.4)
6	27 (26.2 to 27.6)	29.2 (28.8 to 29.7)	31.5 (30.8 to 32.1)
7	29.2 (28.2 to 29.7)	31.4 (31 to 31.8)	34 (33.2 to 34.6)
8	31.2 (30.3 to 31.7)	33.5 (33.1 to 34)	36.4 (35.7 to 37)
9	33.1 (32.2 to 33.7)	35.7 (35.2 to 36.1)	38.7 (38.1 to 39.3)
10	34.8 (34 to 35.6)	37.8 (37.2 to 38.1)	40.9 (40.2 to 41.5)
11	36.5 (35.7 to 37.4)	39.7 (39.1 to 40.1)	42.8 (42.2 to 43.5)
12	38.1 (37.2 to 39)	41.4 (40.8 to 41.8)	44.4 (43.9 to 45)
13	39.4 (38.4 to 40.2)	42.6 (42.2 to 43.1)	45.6 (45.2 to 46.1)
14	40.4 (39.2 to 41.1)	43.5 (43.1 to 44)	46.4 (46.1 to 46.9)
15	41 (39.8 to 41.8)	44 (43.6 to 44.5)	46.9 (46.4 to 47.4)
16	41.2 (40 to 42)	44.3 (43.8 to 44.7)	47.2 (46.6 to 47.6)
17	41.2 (40 to 42.1)	44.3 (43.8 to 44.7)	47.2 (46.6 to 47.6)
18	41.2 (40 to 42.1)	44.3 (43.8 to 44.7)	47.2 (46.6 to 47.7)

*The values are given as the estimate, with the 95% CI in parentheses.

TABLE III Male Femoral, Tibial, and Leg Lengths ➤

Age *(yr)*	Femoral Length* *(cm)* 10th Percentile	50th Percentile	90th Percentile
2	17.4 (16.9 to 18.1)	19 (18.7 to 19.4)	20.3 (19.9 to 20.9)
3	20.3 (19.8 to 20.8)	22 (21.7 to 22.4)	23.5 (23.1 to 23.9)
4	22.9 (22.4 to 23.4)	24.8 (24.3 to 25.2)	26.5 (26 to 26.9)
5	25.2 (24.8 to 25.8)	27.2 (26.7 to 27.8)	29.2 (28.7 to 29.7)
6	27.4 (27 to 28)	29.3 (28.9 to 30)	31.7 (31.1 to 32.5)
7	29.4 (28.9 to 29.9)	31.3 (30.9 to 32)	34.1 (33.5 to 35.1)
8	31.3 (30.6 to 31.8)	33.3 (32.9 to 33.9)	36.4 (35.8 to 37.6)
9	33.3 (32.5 to 33.7)	35.2 (34.8 to 35.8)	38.7 (38 to 39.9)
10	35.2 (34.4 to 35.7)	37.4 (36.8 to 37.9)	40.9 (40.3 to 42.1)
11	37.2 (36.2 to 37.7)	39.6 (39 to 40.1)	43.2 (42.5 to 44.2)
12	39.2 (38 to 39.6)	41.7 (41.1 to 42.2)	45.5 (44.6 to 46.4)
13	41 (39.8 to 41.5)	43.7 (43.1 to 44.3)	47.4 (46.5 to 48.4)
14	42.6 (41.4 to 43.3)	45.5 (44.8 to 46.1)	49.1 (48.2 to 50.1)
15	43.9 (42.7 to 44.6)	46.9 (46.3 to 47.4)	50.4 (49.5 to 51.3)
16	44.6 (43.2 to 45.3)	47.7 (47.1 to 48.2)	51.4 (50.1 to 52)
17	44.8 (43.3 to 45.7)	48 (47.2 to 48.9)	51.6 (50.2 to 52.6)
18	44.8 (43.3 to 45.9)	48 (47.2 to 49.2)	51.7 (50.2 to 52.9)

*The values are given as the estimate, with the 95% CI in parentheses.

TABLE II (*continued*)

Tibial Length* *(cm)*			Leg Length* *(cm)*		
10th Percentile	50th Percentile	90th Percentile	10th Percentile	50th Percentile	90th Percentile
14 (13 to 14.5)	15.2 (14.9 to 15.5)	16.3 (15.9 to 17.1)	31.4 (29.8 to 32.3)	34.1 (33.6 to 34.7)	36.4 (35.7 to 38.2)
16.1 (15.2 to 16.6)	17.5 (17.1 to 17.9)	18.8 (18.5 to 19.5)	36 (34.7 to 36.9)	39.2 (38.6 to 39.8)	41.8 (41.3 to 43.2)
18 (17.2 to 18.6)	19.6 (19.2 to 20.1)	21.2 (21 to 21.8)	40.4 (39.1 to 41.4)	44.1 (43.2 to 44.7)	47.2 (46.4 to 48.3)
19.8 (19.2 to 20.5)	21.7 (21.3 to 22.2)	23.6 (23.3 to 24.1)	44.8 (43.4 to 45.6)	48.7 (47.7 to 49.3)	52.5 (51.5 to 53.3)
21.6 (21 to 22.2)	23.6 (23.2 to 24)	25.8 (25.4 to 26.3)	48.9 (47.5 to 49.7)	53 (52.1 to 53.6)	57.4 (56.2 to 58.1)
23.3 (22.7 to 23.9)	25.4 (25.1 to 25.8)	27.9 (27.5 to 28.4)	52.8 (51.3 to 53.7)	57.1 (56.2 to 57.7)	62 (60.9 to 62.8)
25 (24.4 to 25.6)	27.2 (26.9 to 27.7)	30 (29.5 to 30.4)	56.5 (55 to 57.5)	61.1 (60.3 to 61.7)	66.4 (65.3 to 67.4)
26.6 (25.9 to 27.2)	29.1 (28.7 to 29.5)	31.9 (31.5 to 32.3)	60 (58.5 to 61.1)	65 (64.2 to 65.7)	70.6 (69.6 to 71.6)
28.2 (27.5 to 28.8)	30.9 (30.4 to 31.3)	33.8 (33.2 to 34.1)	63.3 (61.7 to 64.6)	68.7 (67.9 to 69.5)	74.4 (73.5 to 75.5)
29.7 (29 to 30.3)	32.5 (32 to 32.9)	35.3 (34.8 to 35.7)	66.5 (64.7 to 67.7)	72 (71.2 to 73)	77.8 (76.9 to 78.9)
31 (30.3 to 31.6)	33.7 (33.3 to 34.2)	36.7 (36.1 to 37)	69.2 (67.2 to 70.4)	74.8 (74 to 75.9)	80.5 (79.8 to 81.6)
32.1 (31.4 to 32.7)	34.6 (34.2 to 35.2)	37.6 (37 to 37.9)	71.5 (69 to 72.7)	77 (76.2 to 78)	82.8 (81.9 to 83.9)
32.8 (32.1 to 33.4)	35.1 (34.8 to 35.7)	38.2 (37.6 to 38.6)	73.2 (70.4 to 74.5)	78.5 (77.7 to 79.3)	84.2 (83.2 to 85.5)
33.2 (32.4 to 33.8)	35.4 (35 to 36)	38.4 (37.8 to 39.1)	74.3 (71.1 to 75.6)	79.4 (78.5 to 80.1)	85 (83.9 to 86.4)
33.4 (32.4 to 34)	35.5 (35.1 to 36.1)	38.5 (37.9 to 39.3)	74.7 (71.4 to 76.2)	79.8 (78.9 to 80.4)	85.4 (84.1 to 86.9)
33.4 (32.4 to 34)	35.6 (35.1 to 36.2)	38.5 (37.9 to 39.3)	74.8 (71.5 to 76.3)	79.8 (79 to 80.7)	85.4 (84.2 to 87)
33.4 (32.4 to 34)	35.6 (35.1 to 36.2)	38.5 (37.9 to 39.3)	74.8 (71.5 to 76.3)	79.8 (79 to 80.7)	85.4 (84.2 to 87)

TABLE III (*continued*)

Tibial Length* *(cm)*			Leg Length* *(cm)*		
10th Percentile	50th Percentile	90th Percentile	10th Percentile	50th Percentile	90th Percentile
14.3 (13.9 to 14.7)	15.5 (15.3 to 15.7)	16.8 (16.2 to 17.3)	31.9 (30.6 to 32.9)	34.5 (33.9 to 35.1)	37.5 (36.2 to 38.6)
16.5 (16.1 to 16.9)	17.9 (17.6 to 18.1)	19.4 (18.9 to 19.7)	36.7 (35.6 to 37.6)	39.8 (39.1 to 40.3)	42.8 (41.7 to 43.6)
18.4 (18.1 to 18.9)	20.1 (19.7 to 20.4)	21.7 (21.4 to 22.1)	41.2 (40.2 to 42.1)	44.7 (43.9 to 45.3)	48.1 (46.9 to 48.8)
20.2 (19.9 to 20.8)	22.1 (21.6 to 22.4)	23.9 (23.6 to 24.4)	45.3 (44.4 to 46.3)	49.2 (48.3 to 49.8)	53 (51.8 to 54)
22 (21.5 to 22.5)	23.9 (23.4 to 24.3)	26 (25.7 to 26.5)	49.3 (48.4 to 50.2)	53.3 (52.4 to 54.1)	57.7 (56.5 to 59)
23.6 (22.9 to 24.1)	25.6 (25.2 to 26)	28 (27.5 to 28.5)	53 (52 to 53.9)	57 (56.2 to 58.2)	62.1 (61 to 63.8)
25.1 (24.5 to 25.6)	27.2 (26.9 to 27.7)	29.8 (29.4 to 30.4)	56.6 (55.7 to 57.4)	60.7 (59.9 to 62)	66.4 (65.3 to 68.3)
26.6 (26 to 27.1)	28.8 (28.5 to 29.5)	31.6 (31.2 to 32.2)	60.1 (59.2 to 60.9)	64.3 (63.5 to 65.6)	70.5 (69.4 to 72.6)
28.2 (27.6 to 28.6)	30.5 (30.2 to 31.2)	33.5 (33 to 34)	63.7 (62.8 to 64.4)	68.1 (67.3 to 69.4)	74.6 (73.4 to 76.7)
29.8 (29.3 to 30.2)	32.3 (31.9 to 33)	35.4 (34.9 to 35.9)	67.4 (66.3 to 68)	71.9 (71 to 73.1)	78.7 (77.5 to 80.7)
31.3 (30.9 to 31.8)	33.9 (33.5 to 34.7)	37.2 (36.7 to 37.8)	70.9 (69.7 to 71.7)	75.6 (74.7 to 76.9)	82.5 (81.2 to 84.5)
32.8 (32.4 to 33.4)	35.4 (34.9 to 36.1)	38.9 (38.1 to 39.6)	74.1 (73 to 75.2)	79 (78.1 to 80.3)	86 (84.6 to 88.1)
34.1 (33.7 to 34.8)	36.7 (36.2 to 37.4)	40.3 (39.2 to 41.1)	77 (75.9 to 78.1)	81.9 (81.1 to 83.4)	89.1 (87.3 to 91.1)
35.2 (34.6 to 35.8)	37.7 (37.3 to 38.4)	41.5 (40.1 to 42.4)	79.3 (78.2 to 80.3)	84.3 (83.6 to 85.6)	91.5 (89.2 to 93.5)
35.9 (35 to 36.6)	38.4 (38 to 39)	42.3 (40.7 to 43.5)	80.7 (79 to 81.8)	86 (85 to 86.9)	93.3 (89.9 to 95.3)
36.2 (35.1 to 37.2)	38.7 (38.2 to 39.6)	42.7 (40.8 to 44.6)	81.5 (79.1 to 82.8)	86.9 (85.2 to 88.3)	94.1 (90.2 to 96.7)
36.4 (35.1 to 37.7)	39 (38.2 to 40.1)	43 (40.8 to 45.1)	81.9 (79.1 to 83.5)	87.4 (85.2 to 89.4)	94.5 (90.2 to 97.4)

TABLE IV Femoral and Tibial Length Comparisons Between the GA Study and the Current Study*

	Male Patients *(cm)*						Female Patients *(cm)*					
	Median in GA Cohort		Median in Current Study				Median in GA Cohort		Median in Current Study			
Age *(yr)*	Femoral	Tibial	Femoral	Tibial	Femoral Difference	Tibial Difference	Femoral	Tibial	Femoral	Tibial	Femoral Difference	Tibial Difference
2	NA	NA	19	15.5	NA	NA	NA	NA	18.9	15.2	NA	NA
3	NA	NA	22	17.9	NA	NA	NA	NA	21.8	17.5	NA	NA
4	NA	NA	24.8	20.1	NA	NA	NA	NA	24.4	19.6	NA	NA
5	25.6	20.3	27.2	22.1	1.6	1.8	26.1	20.4	26.9	21.7	0.8	1.3
6	28	21.9	29.3	23.9	1.3	2	28.2	22.4	29.2	23.6	1	1.2
7	29.8	23.5	31.3	25.6	1.5	2.1	30.2	24.3	31.4	25.4	1.2	1.1
8	32.1	25.1	33.3	27.2	1.2	2.1	31.9	25.2	33.5	27.2	1.6	2
9	34.1	26.5	35.2	28.8	1.1	2.3	34	26.9	35.7	29.1	1.7	2.2
10	35.7	28	37.4	30.5	1.7	2.5	35.6	28.2	37.8	30.9	2.2	2.7
11	37.4	29.2	39.6	32.3	2.2	3.1	37.4	29.4	39.7	32.5	2.3	3.1
12	39.3	30.6	41.7	33.9	2.4	3.3	39.2	31	41.4	33.7	2.2	2.7
13	41.2	32.8	43.7	35.4	2.5	2.6	41.2	32.8	42.6	34.6	1.4	1.8
14	43.5	34.6	45.5	36.7	2	2.1	41.8	33	43.5	35.1	1.7	2.1
15	45.4	36	46.9	37.7	1.5	1.7	42.3	33	44	35.4	1.7	2.4
16	46.6	37	47.7	38.4	1.1	1.4	42.3	33.6	44.3	35.5	2	1.9
17	45.8	37	48	38.7	2.2	1.7	NA	NA	44.3	35.6	NA	NA
18	45.8	37	48	39	2.2	2	NA	NA	44.3	35.6	NA	NA
Mean					1.8	2.2					1.7	2

*The differences in femoral and tibial lengths were computed by subtracting the median length in the GA cohort[4] from the median length in the current institutional cohort. NA = not applicable.

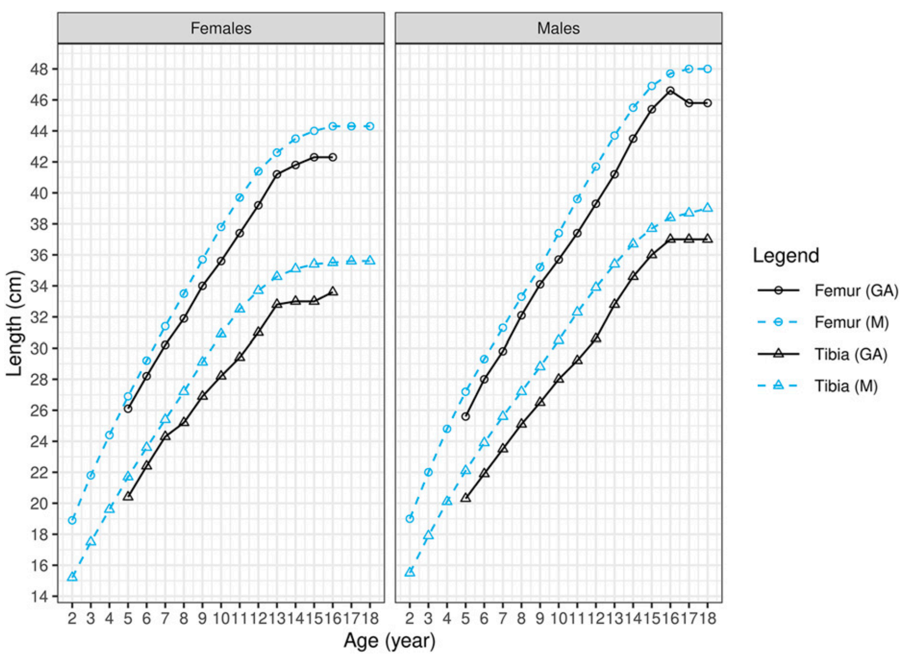

Fig. 7

The 50th percentile femoral (circle) and tibial (triangle) lengths of the 2 to 18-year-old female and male patients in our institutional cohort (denoted by M and dashed lines) compared with the available 50th percentile femoral and tibial lengths of female and male patients in the Green-Anderson cohort (denoted by GA and solid lines). (Data for this figure were obtained from: Anderson M, Green WT. Lengths of the femur and the tibia; norms derived from orthoroentgenograms of children from 5 years of age until epiphysial closure. Am J Dis Child [1911]. 1948 Mar;75[3]:279-90.)

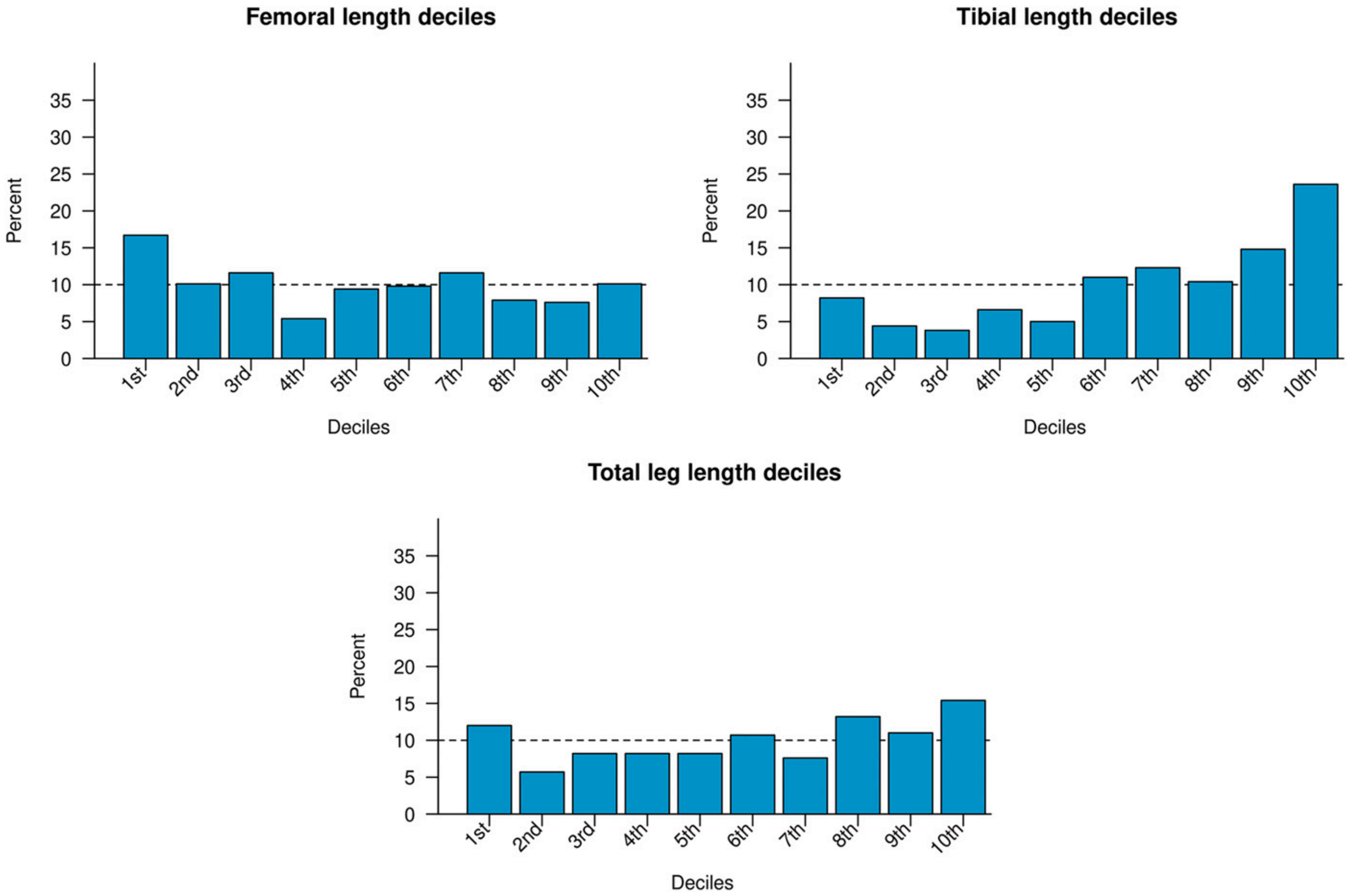

Fig. 8
Our model was validated by assessing the calibration using a novel cohort of patients treated from 2021 to 2022. These plots show the percentage of the validation cohort falling into the corresponding deciles from our original analysis. A perfect calibration would show 10% in each category.

External Validation

We undertook additional work to validate our model by assessing the calibration using a new cohort of 318 patients treated from 2021 to 2022 at our center who were not included in the original study and met the same inclusion criteria. The percentages of the validation cohort falling into the deciles from our original analysis were plotted. A perfect calibration would show 10% in each decile. However, given the sample size, we would expect some variability. Interestingly, there was a greater proportion of longer tibiae and, to a lesser extent, total leg lengths, again highlighting that the traditional GA data are likely underestimating leg lengths (Fig. 8).

Discussion

Green and Anderson's published work was a major contribution to the understanding of skeletal growth (Table V)[1-4,15]. Their 1947 study involved approximately 700 children, 87% of

TABLE V Overview of the GA Growth Data*

			Female		Male	
Study	No. of Patients	Patients with Polio	Patient Ages *(yr)*	No. of Time Points	Patient Ages *(yr)*	No. of Time Points
Green and Anderson[1] (1947)	Approximately 700	87%	5 to 16	12	5 to 18	14
Anderson and Green[4] (1948)	255	213 (84%)	5 to 16	12	5 to 18	14
Anderson et al.[2] (1963)	100	49 (49%)	8 to 18	11	8 to 18	11
Anderson et al.[3] (1964)	134	NA	1 to 18	18	1 to 18	18
Current study	700	0	2 to 18	17	2 to 18	17

*NA = not available.

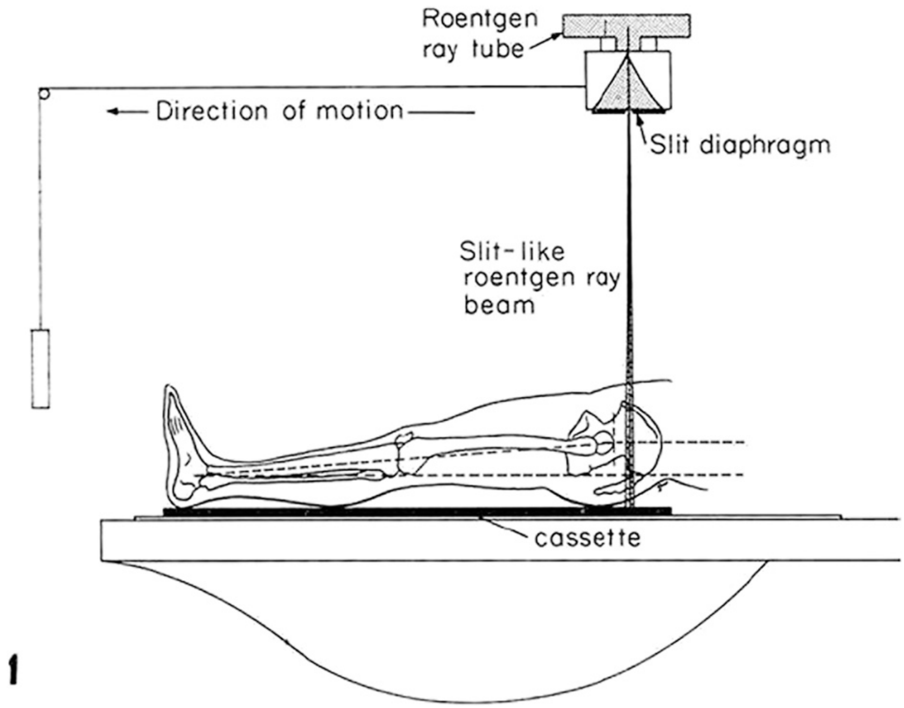

Fig. 9
The slit-like x-ray beam moved down the length of the patient's legs from the hips to the ankles. Tube motion and exposure are continuous and simultaneous. (Reprinted from: Pugh DG, Winkler NT, Scanography for Leg-Length Measurement: An Easy Satisfactory Method, Radiology, 1966, Vol. 87, No. 1, pages 130 to 133, with permission from The Radiological Society of North America.)

whom had paralytic poliomyelitis affecting 1 lower limb. Their work also included serial orthoroentgenograms made in 158 normal children[1]. Although the data were collected longitudinally and radiographs were made every year until skeletal maturity, the data set is now considered to have weaknesses. The individual patient data and radiographs are not available for further analysis and study. Furthermore, the study cohort was relatively homogenous and does not represent the heterogeneous nature of modern society. In addition, most of their patients had unilateral poliomyelitis. Despite the limitations of the GA cohort, the Moseley straight-line method and Paley multiplier method developed in recent decades still rely on the original GA data[16,17]. It is essentially impossible to repeat a study similar to the GA study as concerns about radiation exposure for research purposes limits the ability to obtain consecutive annual radiographs in normal children.

Longitudinal data (i.e., data collected sequentially at multiple time points) following a substantial cohort such as in the GA data set used by Moseley[17] and Paley et al.[16] are often summarized using means and standard deviations[3]. Data from cross-sectional studies conducted at a single time point are typically summarized using more robust measures such as medians and percentiles. Longitudinal studies can be expensive and follow only a small number of individuals. Thus, the modern method of developing growth charts involves a cross-sectional study to demonstrate the distribution of anthropometric characteristics. That can be done by splitting the data into consecutive age groups and reporting the percentiles in every single group[9]. This is known as generalized additive models for location, scale, and shape (GAMLSS)[8,18], which was a modification and generalization of a previously described lambda-mu-sigma (LMS) method[19]. This method was utilized by the WHO and the CDC to develop the modern growth charts[7,8,20]. For our study and data available, we used quantile regression with smoothing splines to estimate the conditional median and other quantiles of the femoral, tibial, and leg lengths.

Since the GA data set, other growth data for the femur and the tibia have rarely been reported, with the exception of the data by Beumer et al., who developed a new straight-line graph modifying Moseley's straight-line graph by collecting radiographic data from 182 Dutch children[21]. In comparison with the data of Anderson et al., they noted longer femora and tibiae in the Dutch children at most ages. However, the Dutch people are known to be among the tallest groups in the world, which may limit the generalizability of these data[22]. To the best of our knowledge, the present study is the first investigation reporting normative growth charts of femoral and tibial lengths in twenty-first-century U.S. children using methods for modern growth chart development.

In the present study, we used slit scanograms and standing slot-scanning radiographs to measure limb lengths. In our center, we have used the technique of leg-length measurement by slit scanography described by Pugh and Winkler[11], in which the x-ray beam is collimated to a narrow slit and the tube moves over the patient's lower extremities (Fig. 9). The accuracy of a slit scanogram in measuring limb length has been widely investigated[13,14,23-25]. The biplanar slot-scanning radiograph technique has been widely used in orthopaedic practices to assess limb length[26-29]. Overall, the 50th percentiles of the tibial and femoral lengths in the boys and girls in the present study were 0.8 to 3.3 cm (1% to 11%) longer than those in the GA data set.

Although the growth data set first published by Green and Anderson in 1947 was based on skeletal age, the most widely used growth-remaining charts presented in 1964 were based on chronological age. Moreover, the methods of Moseley[17] and Paley et al.[16] both used the 1964 data from Anderson et al.[3], which were based on chronological age. However, Aguilar et al. had compared the accuracy of the Moseley straight-line graph method and the Paley multiplier method, and did not find significant differences between the predictions based on chronological and skeletal ages[30,31]. Little et al. evaluated different methods for predicting the timing of epiphysiodesis, including the GA, Menelaus, and Moseley methods. They revealed that, irrespective of whether skeletal or chronological age was used, all of the methods had similar accuracy. The mean errors approached 1.0 cm in each method. According to their findings, the use of serial Greulich and Pyle skeletal-age data did not improve accuracy[32]. Previous studies have shown poor agreement in the assessment of hand bone age[33-35].

In the past decades, there has been a noticeable increase in the height of both boys and girls worldwide[36]. According to the most recent published data from the CDC's National Center for Health Statistics (NCHS), the mean heights of U.S.-born children have been increasing over time[5,37]. Using the databases of the National Health Examination Surveys (NHES) and the National Health and Nutrition Examination Surveys (NHANES), the studies showed that the mean height of a child in the United States increased between the 1960s and 2002, with the mean height of boys 6 to 11 years of age increasing 2.03 cm and that of girls 6 to 11 years of age increasing 1.52 cm. Among 12 to 17-year-old adolescents, height increased 1.78 cm for boys and 0.76 cm for girls[5,37]. A trend of increasing growth is a marker of public health and is associated with improvements in income, socioeconomic status, infection prevention, and nutrition[6,36]. This has resulted in the majority of today's children being charted above average on the GA bone length charts and highlights the potential value of introducing new charts based on updated data. Changing social and environmental conditions have also affected body proportions over the past century. The historical data showed increases in body height in the past decades. The mean standing height increased approximately 2 cm from 1960 to 2002 according to the most recent CDC data[37]. Some authors have noted greater proportional increases in leg length compared with sitting height[38]. Two widely used growth prediction methods, the Moseley straight-line graph and Paley multiplier methods, were developed on the basis of the GA data reported in 1964[3]. The 1964 GA data summarized bone length with means and standard deviations, whereas our data in the current study used medians and percentiles. Nevertheless, we still observed longer bone lengths in the patients in this study. Thus, when the Moseley straight-line graph and Paley multiplier methods are used, there is potential inaccuracy in predicting the timing for epiphysiodesis.

The present study had several limitations. In contrast to the GA data, our study did not follow the same individuals throughout the period of growth until maturity. The growth data in the present study excluded patients with any systemic or endocrinologic diseases, such as juvenile idiopathic arthritis, that may affect normal skeletal growth. Additionally, it was not possible to compare the bone segment lengths between individuals in the GA data set and our cohort with the same methodology because of a lack of the GA raw data. Hand radiographs to assess bone age were not routinely made in our cohort. Therefore, some patients with substantial differences between their chronological age and their skeletal age might be included in our cohort, and we could not evaluate the impact of skeletal age on our findings. Future work could study mean leg lengths in additional patient populations with hand bone ages available for review. Moreover, the cohort in our study may not be representative of the general U.S. population of children; rather, it reflects the patients seen in a specific pediatric orthopaedic practice. The racial and ethnic composition of our cohort reflects patients presenting in our institution, which is a predominantly White population, reflecting the demographic characteristics of the Midwestern U.S. population. There might be different patterns of growth charts in areas with different ethnic distributions. Therefore, well-designed multicenter studies with the same standardized imaging method might be needed to clarify our findings so that they are widely applicable.

In conclusion, although this study does not necessarily reflect the racial, ethnic, or socioeconomic demographic characteristics of the entire United States, it evaluates standardized radiographs from a single center with a population of patients who underwent an incidental scanogram or follow-up for a unilateral condition. We found that femoral and tibial lengths at nearly all time points were 1 to 3 cm longer than the GA data. Thus, the use of the GA data for timed epiphysiodesis could result in an underestimation of expected childhood growth. ■

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