Lower Limb Alignment in Children

Reference Values Based on a Full-Length Standing Radiograph

Sanjeev Sabharwal, MD, Caixia Zhao, MD, and Michele Edgar, PA-C

Background: A full-length standing anteroposterior radiograph of the entire lower extremity has become the standard imaging modality for assessing lower limb alignment. Although reference values of frontal plane deformity parameters based on adult subjects have been established, such values may not be applicable to the pediatric population. The purpose of our study was to establish the reference values of frontal plane alignment and joint orientation angles in children based on a standing full-length radiograph.

Methods: A database at a single institution was searched for patients who were aged between 1 and 18 years at the time of undergoing a standing full-length radiograph of the lower extremities. Radiographic analysis of lower extremities without any abnormalities was performed by a single observer. Mechanical axis deviation, lateral distal femoral angle (LDFA), medial proximal tibial angle (MPTA), tibiofemoral angle, joint line convergence angle, and mechanical axis station were calculated at yearly intervals. The data were summarized using descriptive statistics, and simple regression analysis was performed to determine the relationship between the patients' age and the magnitude of LDFA and MPTA.

Results: A total of 354 unaffected lower extremities in 253 children were analyzed. Between the ages of 1 and 2 years, the tendency for varus alignment of the lower limb was related to the varus orientation of the distal femur with a mean LDFA of 95 degrees (95% confidence interval [CI], 93–97 degrees). By the age of 3 years, the limb alignment changed to valgus related to a combination of decreasing varus orientation of the distal femur and a mild increase in valgus orientation of the proximal tibia with the mean MPTA changing from 89 degrees (95% CI, 88–90 degrees) to 91 degrees (95% CI, 90–92 degrees). After the age of 7 years, all joint orientation angles were noted to be within the range of reference values that are available for the adult population. Despite changes in limb alignment with growth, the mean mechanical axis of the lower extremity remained within the central half of the knee joint in children older than 1 year of age.

Conclusions: The change in alignment of the lower limb from 1 to 4 years of life from varus to valgus is primarily related to a progressive decrease in varus orientation of the distal femur. In children younger than 7 years old, age-specific reference values for joint orientation angles of the lower extremity should be used instead of values derived from adult subjects.

From the Department of Orthopedics, University of Medicine and Dentistry of New Jersey, New Jersey Medical School, Newark, NJ.

This study was conducted at the University of Medicine and Dentistry of New Jersey, New Jersey Medical School, Newark, NJ.

One of the authors (SS) received financial support for this study from Smith & Nephews.

Reprints: Sanjeev Sabharwal, MD, Professor, Department of Orthopedics, University of Medicine and Dentistry–New Jersey Medical School, Doctor's Office Center, 90 Bergen St, Suite 7300, Newark, NJ 07103. E-mail: sabharsa@umdnj.edu.

Level of Evidence: Diagnostic level II.

Key Words: lower limb alignment, children, standing radiograph, mechanical axis deviation, reference values

(*J Pediatr Orthop* 2008;28:740–746)

It is well recognized that the physiological alignment of the lower limbs changes during the first few years of life.[1,2] However, the established reference values of pediatric lower limb alignment are based on clinical[1] and radiographic[2] measurements limited to the tibiofemoral angle (TFA). Although such an angular measurement is an approximation of lower limb alignment, the measurement of the TFA alone does not allow for a comprehensive analysis of the lower extremity. Moreover, it can be difficult to reproducibly assess the TFA in young children because of the varus bow of the proximal femoral shaft[2] and physiological internal tibial torsion that is often associated with a tendency to externally rotate the knee.

Currently, a full-length standing anteroposterior (AP) radiograph of the entire lower extremity with the patella facing anteriorly has become the standard imaging modality for assessing lower limb alignment, joint orientation angles, and length discrepancy.[3,4] Based on such a radiograph in adult subjects, several authors have documented reference values of lower limb alignment and joint orientation angles.[3,5–7] However, we were unable to find a similar study for the pediatric population.

The purpose of our study was to establish the values of normal frontal plane alignment and joint orientation angles based on a standing full-length radiograph of the lower extremity in children. Our hypothesis was that the frontal plane alignment and joint orientation angles of the lower limb as determined by a standing full-length radiograph changes with age in the pediatric population. Thus, the reference values of these radiographic parameters in children may be different from the currently established standards, which are based on adult subjects.

METHODS

After getting approval from our institutional review board, a database of all radiographs done in the Department of Radiology between April 2000 and October 2007 was searched. Patients who were younger than 18 years at the time of undergoing a standing full-length radiograph of the lower extremities were identified. Outpatient medical records of the identified subjects were reviewed for demographic information including the patients' date of birth, sex, and the reason for obtaining the standing radiograph. Based on the review of radiographs and clinical records, only those extremities without any radiographic abnormalities or clinical concerns were included. Children with a history of any underlying neuromuscular disorder such as cerebral palsy were excluded. Radiographs were also excluded if the entire lower extremity from the hip to the ankle joint was not visualized, if there was an overlying external fixator or cast on the contralateral extremity,[8] if the second radiograph was done within 6 months of the previous one, if the radiograph was done with the child supine or if greater than 60% overlap of the proximal fibula at the level of the proximal tibial metaphyses was noted,[9] suggesting lack of a *patella forward* position. Because children are typically unable to stand independently until the age of 1 year, the full-length radiographs done in this age group were routinely excluded.

The full-length standing AP radiograph of both lower extremities was taken using a standardized computed radiography technique[4] with the patient facing the radiographic tube and both patellas pointing anteriorly (Fig. 1). The minimum patient-to-tube distance was 203 cm and was increased for taller individuals. Patients were instructed to place full and equal weight on both lower extremities, without holding on to any supportive device. If a limb length discrepancy was noted on clinical examination, an attempt was made to level the pelvis with an appropriate-sized lift placed under the short limb while taking the standing radiograph.

The radiographic analysis included assessment of the mechanical axis deviation (MAD), mechanical lateral distal femoral angle (LDFA[m]), medial proximal tibial angle (MPTA), modified tibiofemoral angle (TFA), joint line convergence angle (JLCA), and the relationship of the mechanical axis line to the center of the knee joint (Fig. 1).[3,10] Mechanical axis deviation was calculated in millimeters as the perpendicular distance from the center of the femoral condyles to the mechanical axis line connecting the center of the femoral head to the center of the talar dome. The LDFA(m) was measured as the lateral angle between the longitudinal line connecting the center of the proximal femoral epiphyses and the center of the distal femoral condyles and the transverse line tangential to the most distal points on the convexity of the femoral condyles. A larger LDFA(m) denotes an increasing varus orientation of the distal femur. The MPTA was measured as the medial angle between the transverse line tangential to the proximal tibial epiphyses and the longitudinal line connecting the center of the proximal tibial epiphyses to the midwidth of the talus at the ankle mortise. A larger MPTA indicates an increasing valgus orientation of the proximal tibia. Due to insufficient ossification of the proximal tibial epiphyses in children younger than 10 years, the transverse line drawn at the level of the tibial epiphyses was made parallel to the growth plate of the proximal tibia for determining the MPTA. Because of the varus bowing of the proximal femoral shaft in young children, a modified TFA was measured between the middiaphyseal line of the distal third of the femoral shaft and the middiaphysis of the tibia. The JLCA was measured in degrees as the angle between the distal femoral condyles and the proximal tibial epiphyses. In children younger than 10 years, the transverse line drawn at the level of the tibial epiphyses was made parallel to the growth plate of the proximal tibia and used to measure the JLCA. If the apex of the JLCA was medial, it was denoted as varus, indicated by a plus sign, and if lateral, it was denoted as valgus, indicated by a minus sign. The mechanical axis of the limb was also quantified based on the relationship of the line connecting the center of the femoral head to the center of the talar dome.[10] The knee was divided into 4 stations (quadrants), with the medial 2 stations designated as +1 and +2, representing varus alignment and the lateral stations as −1 and −2, representing valgus alignment of the mechanical axis line, with station 1 being closer to the center of the knee joint (Fig. 1).

All of the radiographs were analyzed by a fellowship-trained pediatric orthopaedic surgeon (S.S.) using a digital cursor at a Picture Archiving and Communications System (PACS) workstation (Centricity PACS 2.0, GE Medical Systems Information Technologies, Milwaukee, Wis). Intraobserver reliability for measuring the various frontal plane deformity parameters was determined by using a randomized set of 30 standing radiographs that were measured by the same examiner (S.S.) a few weeks apart. The intraobserver reliability was recorded using the criteria of Winer[11]—an intraclass coefficient (ICC) of 0 to 0.24 reflects absent to poor,

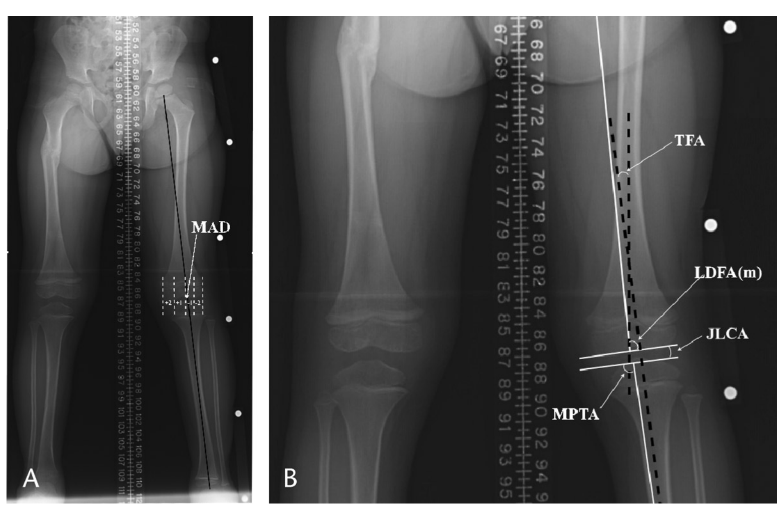

FIGURE 1. A standing full-length AP radiograph of a 5-year-old boy 5 months after an isolated right-sided femoral shaft fracture. The uninjured left lower extremity was used to measure the frontal plane deformity parameters. A, Landmarks used for measuring the MAD and the mechanical axis station indicating the relationship of the mechanical axis line to the center of the knee joint. B, Landmarks used for measuring the LDFA(m), MPTA, TFA, and JLCA.

0.25 to 0.49 low, 0.50 to 0.69 fair to moderate, 0.7 to 0.89 good, and 0.9 to 1.0 excellent reliability. The mean absolute difference between the 2 sets of calculations was also assessed for each of the radiographic parameters.

Statistical analysis was performed using SAS version 9.1 software (SAS Institute Inc, Cary, NC). For the purpose of analysis, the subjects in this study were divided into 17 groups based on their chronological age at the time of the standing radiograph, from 1 to 18 years, at yearly intervals. The data were summarized using descriptive statistics of mean, SD, SE, and 95% confidence interval (95% CI).

Simple regression analysis was performed to determine the relationship between the patients' age and the magnitude of LDFA and MPTA. The α level for all analyses was set at $P < 0.05$.

To minimize the effect of any confounding variables related to the children who had both limbs eligible for inclusion in the study, only 1 of the 2 limbs was randomly selected for the statistical analysis. The possible effect of other variables such as the underlying etiology (trauma vs others), side (right vs left lower extremity), and sex (male vs female) on the values of various frontal plane alignment parameters was assessed using unpaired t test with the Bonferroni correction.

RESULTS

A total of 2399 full-length standing AP radiographs were performed on 1174 individuals between April 2000 and October 2007 at our institution. These patients included 697 adults (1282 radiographs) and 477 children (1117 radiographs). Based on the inclusion criteria, 253 children (354 radiographs) were entered into the study. Fifty-two of these 253 children had 101 additional standing radiographs, ranging from 1 to 7 additional radiographs per individual, taken a minimum of 6 months apart. There were 196 right-sided and 158 left-sided lower extremities. Thus, a total of 354 unaffected lower extremities in 253 children were the subject of this study (Table 1).

TABLE 1. Age Distribution

Age, y	No. Patients	No. Radiographs
1 – <2	17 (7)	17 (5)
2 – <3	17 (7)	21 (6)
3 – <4	17 (7)	24 (7)
4 – <5	13 (5)	17 (5)
5 – <6	9 (4)	14 (4)
6 – <7	9 (4)	13 (4)
7 – <8	18 (7)	19 (5)
8 – <9	14 (6)	22 (6)
9 – <10	13 (5)	20 (6)
10 – <11	21 (8)	29 (8)
11 – <12	16 (6)	24 (7)
12 – <13	23 (9)	36 (10)
13 – <14	16 (6)	23 (6)
14 – <15	20 (8)	23 (6)
15 – <16	7 (3)	13 (4)
16 – <17	13 (5)	23 (6)
17 – <18	10 (4)	16 (5)
Total	253 (100)	354 (100)

Details of the number (percentage) of patients and standing radiographs of unaffected lower limbs in each age group that were used for radiographic analysis.

Data are presented as no. (%).

TABLE 2. MAD Distribution by Age Group

Age, y	Mean, mm*	SD	SE	95% CI, mm*
1 – <2	5.2	8.6	2.0	0.8 to 9.7
2 – <3	−4.6	5.5	1.2	−7.1 to −2.0
3 – <4	−3.7	5.5	1.1	−6.0 to −1.3
4 – <5	−4.6	3.4	0.8	−6.3 to −2.8
5 – <6	−6.3	4.5	1.2	−8.9 to −3.7
6 – <7	−4.7	6.2	1.7	−8.5 to −0.9
7 – <8	−2.2	7.1	1.6	−5.6 to 1.2
8 – <9	0.9	5.4	1.1	−1.5 to 3.3
9 – <10	−0.2	6.9	1.5	−3.5 to 3.0
10 – <11	0.7	6.4	1.2	−1.7 to 3.1
11 – <12	−1.0	5.8	1.2	−3.4 to 1.4
12 – <13	−0.3	8.1	1.3	−3.0 to 2.4
13 – <14	−0.1	8.2	1.7	−3.6 to 3.5
14 – <15	−1.4	9.3	1.9	−5.4 to 2.6
15 – <16	2.4	7.3	2.0	−1.9 to 6.8
16 – <17	3.3	8.1	1.6	−0.1 to 6.9
17 – <18	−0.1	7.9	1.9	−4.3 to 4.0

Details of the values of the MAD based on child's age. A positive value (+) indicates varus and a negative value (−) indicates valgus alignment of the lower limb.

*Positive value, medial; negative value, lateral.

The age of the subjects ranged from 1.1 year to 17.9 years (mean, 9.4 years). There were 149 males and 104 females including 131 blacks (52%), 76 Hispanics (30%), 34 whites (13%), 8 Asians (3%), and 4 Native Americans (2%). One hundred seven (42%) of the children had a history of trauma isolated to the contralateral lower extremity. The remaining children had a diagnosis of gait abnormality (23%), spinal deformity (1%), congenital shortening (22%), Blount disease (8%), or a skeletal lesion (4%) affecting the contralateral extremity.

The intraobserver reliability for radiographic analysis of frontal plane alignment was found to be good to excellent for all parameters including MAD (ICC, 0.99), LDFA(m) (ICC, 0.92), MPTA (ICC, 0.83), TFA (ICC, 0.92), JLCA (ICC, 0.84), and measurement of MAD station (ICC, 0.99). The mean absolute difference between the 2 sets of measurements obtained a few weeks apart by the same observer (S.S.) was 0.5 mm for MAD and less than 1 degree for each of the angular measurements. The reliability for measuring the proximal fibular overlap was also excellent (ICC, 0.95), with a mean absolute difference of 2% between the 2 sets of observations.

The mean values, SD, SE, and 95% CI of the frontal plane radiographic parameters calculated at yearly intervals from age of 1 to 18 years are detailed in Tables 2–7. Between the ages of 1 and 2 years, the mechanical axis line was medial to the midpoint of the knee joint (station +1) indicating varus alignment of the lower limb. The alignment changed to valgus after the age of 2 years, suggested by the mechanical axis line being just lateral to the midpoint of the knee joint (station −1), and remained so until the age of 7 years. After the age of 7 years up to skeletal maturity, the MAD remained within 4 mm of the midpoint of the knee joint (Table 2).

TABLE 3. LDFA(m) Distribution by Age Group

Age, y	Mean, Degrees	SD	SE	95% CI, Degrees
1 – <2	94.8	3.8	0.9	92.8 – 96.8
2 – <3	90.7	3.4	0.7	89.1 – 92.3
3 – <4	89.0	2.5	0.5	87.9 – 90.0
4 – <5	87.5	2.5	0.6	86.2 – 88.9
5 – <6	88.3	1.1	0.3	87.6 – 89.0
6 – <7	87.7	2.3	0.6	86.3 – 89.1
7 – <8	86.8	2.2	0.5	85.8 – 87.9
8 – <9	88.1	1.9	0.4	87.3 – 89.0
9 – <10	88.1	1.9	0.4	87.1 – 89.0
10 – <11	87.9	1.8	0.3	87.2 – 88.6
11 – <12	87.2	1.8	0.3	86.5 – 88.0
12 – <13	87.0	2.1	0.3	86.3 – 87.7
13 – <14	87.5	1.9	0.4	86.7 – 88.4
14 – <15	87.4	1.9	0.4	86.5 – 88.2
15 – <16	87.7	1.6	0.4	86.7 – 88.7
16 – <17	87.6	1.5	0.3	86.9 – 88.3
17 – <18	87.7	1.6	0.4	86.8 – 88.6

Details of the values of the LDFA(m) based on child's age.

TABLE 5. TFA Distribution by Age Group

Age, y	Mean, Degrees*	SD	SE	95% CI, Degrees*
1 – <2	−3.8	4.2	1.0	−5.9 to −1.6
2 – <3	−9.1	3.0	0.6	−10.5 to −7.7
3 – <4	−9.0	3.2	0.6	−10.3 to −7.6
4 – <5	−8.6	2.0	0.4	−9.6 to −7.6
5 – <6	−9.0	3.3	0.8	−10.9 to −7.0
6 – <7	−7.6	2.0	0.5	−8.8 to −6.3
7 – <8	−6.7	2.6	0.6	−8.0 to −5.5
8 – <9	−6.0	1.9	0.4	−6.9 to −5.2
9 – <10	−6.9	2.5	0.5	−8.1 to −5.7
10 – <11	−6.4	2.1	0.3	−7.2 to −5.6
11 – <12	−6.4	1.7	0.3	−7.1 to −5.7
12 – <13	−6.5	2.3	0.3	−7.3 to −5.7
13 – <14	−6.7	2.4	0.5	−7.8 to −5.7
14 – <15	−6.6	2.6	0.5	−7.7 to −5.4
15 – <16	−5.3	2.1	0.5	−6.6 to −4.0
16 – <17	−5.3	1.7	0.3	−6.0 to −4.6
17 – <18	−5.9	2.2	0.5	−7.1 to −4.7

Details of the values of the modified TFA based on child's age.
*Positive value, varus; negative value, valgus.

With regard to the joint orientation angles between the ages of 1 and 2 years, the tendency for varus alignment of the lower limb was related to the varus orientation of the distal femur (mean LDFA(m) 95 degrees; Table 3). During the next year, between the ages of 2 and 3 years, the limb alignment changed to valgus related to a combination of decreasing varus orientation of the distal femur (mean LDFA[m], 91 degrees) and a mild increase in valgus orientation of the proximal tibia, with the mean MPTA changing from 89 to 91 degrees (Table 4). The mean LDFA(m) remained essentially constant between 87 and 88 degrees in children older than 4 years until skeletal maturity (Table 3). The mean MPTA reached a plateau of 87 to 89 degrees after the age of 7 years until skeletal maturity (Table 4). The modified TFA peaked by the age of 6 years, with a mean of 9 degrees of valgus alignment (Table 5) and remained between 5 and 7 degrees of valgus from the age of 7 years until skeletal maturity. The mean JLCA was 3 degrees lateral between the ages of 1 and 2 years. After the age of 4 years, the JLCA remained between zero and 2 degrees medial until skeletal maturity (Table 6). Simple regression analysis demonstrating the relationship between the patients' age and the magnitude of LDFA and MPTA is shown in Figures 2 and 3.

The effect of etiology (trauma vs others), side (right vs left lower extremity), and sex (male vs female) on the values of various frontal plane alignment parameters revealed a difference of less than or equal to 1 mm in mean MAD and

TABLE 4. MPTA Distribution by Age Group

Age, y	Mean, degrees	SD	SE	95% CI, degrees
1 – <2	89.0	2.8	0.7	87.5 – 90.4
2 – <3	91.3	1.9	0.4	90.4 – 92.0
3 – <4	90.8	1.9	0.3	90.0 – 91.6
4 – <5	90.3	1.8	0.4	89.3 – 91.3
5 – <6	90.3	1.5	0.4	89.4 – 91.2
6 – <7	90.0	1.2	0.3	89.2 – 90.7
7 – <8	88.7	1.6	0.3	87.9 – 89.5
8 – <9	87.9	2.2	0.4	86.9 – 88.8
9 – <10	88.6	2.0	0.4	87.6 – 89.5
10 – <11	88.5	1.7	0.3	87.9 – 89.1
11 – <12	88.2	2.2	0.4	87.3 – 89.2
12 – <13	87.7	1.9	0.3	87.0 – 88.4
13 – <14	88.6	2.2	0.4	87.7 – 89.6
14 – <15	88.6	2.1	0.4	87.7 – 89.6
15 – <16	88.1	1.5	0.4	87.2 – 89.1
16 – <17	87.6	1.6	0.3	86.9 – 88.4
17 – <18	88.1	1.8	0.4	87.1 – 89.1

Details of the values of the MPTA based on child's age.

TABLE 6. JLCA Distribution by Age Group

Age, y	Mean, degrees*	SD	SE	95% CI, degrees*
1 – <2	−3.1	3.1	0.7	−4.8 to −1.5
2 – <3	−2.7	2.6	0.5	−3.9 to −1.5
3 – <4	−0.1	2.4	0.4	−1.0 to 0.9
4 – <5	1.7	1.6	0.3	0.9 to 2.6
5 – <6	0.1	1.5	0.4	−0.7 to 1.0
6 – <7	0.8	1.6	0.4	−0.1 to 1.8
7 – <8	1.5	1.6	0.3	0.8 to 2.3
8 – <9	1.0	1.5	0.3	0.3 to 1.7
9 – <10	1.0	1.5	0.3	0.3 to 1.7
10 – <11	1.4	1.3	0.2	0.9 to 1.9
11 – <12	1.2	1.2	0.2	0.7 to 1.7
12 – <13	1.0	1.2	0.2	0.6 to 1.4
13 – <14	1.3	0.7	0.1	1.0 to 1.7
14 – <15	1.1	1.3	0.2	0.5 to 1.7
15 – <16	1.0	0.8	0.2	0.5 to 1.5
16 – <17	1.0	1.0	0.2	0.5 to 1.4
17 – <18	0.3	0.9	0.2	−0.1 to 0.8

Details of the values of the JLCA based on child's age.
*Positive value, medial; negative value, lateral.

TABLE 7. A Summary Table of Limb Deformity Parameters Based on a Full-length Standing Radiograph of the Unaffected Lower Extremity

	MAD, mm		mLDFA, Degrees		MPTA, Degrees		TFA, Degrees		JLCA, Degrees	
Age, y	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1 – <2	5.2	8.6	94.8	3.8	89.0	2.8	−3.8	4.2	−3.1	3.1
2 – <3	−4.6	5.5	90.7	3.4	91.3	1.9	−9.1	3.0	−2.7	2.6
3 – <4	−3.7	5.5	89.0	2.5	90.8	1.9	−9.0	3.2	−0.1	2.4
4 – <5	−4.6	3.4	87.5	2.5	90.3	1.8	−8.6	2.0	1.7	1.6
5 – <6	−6.3	4.5	88.3	1.1	90.3	1.5	−9.0	3.3	0.1	1.5
6 – <7	−4.7	6.2	87.7	2.3	90.0	1.2	−7.6	2.0	0.8	1.6
7 – <8	−2.2	7.1	86.8	2.2	88.7	1.6	−6.7	2.6	1.5	1.6
8 – <9	0.9	5.4	88.1	1.9	87.9	2.2	−6.0	1.9	1.0	1.5
9 – <10	−0.2	6.9	88.1	1.9	88.6	2.0	−6.9	2.5	1.0	1.5
10 – <11	0.7	6.4	87.9	1.8	88.5	1.7	−6.4	2.1	1.4	1.3
11 – <12	−1.0	5.8	87.2	1.8	88.2	2.2	−6.4	1.7	1.2	1.2
12 – <13	−0.3	8.1	87.0	2.1	87.7	1.9	−6.5	2.3	1.0	1.2
13 – <14	−0.1	8.2	87.5	1.9	88.6	2.2	−6.7	2.4	1.3	0.7
14 – <15	−1.4	9.3	87.4	1.9	88.6	2.1	−6.6	2.6	1.1	1.3
15 – <16	2.4	7.3	87.7	1.6	88.1	1.5	−5.3	2.1	1.0	0.8
16 – <17	3.3	8.1	87.6	1.5	87.6	1.6	−5.3	1.7	1.0	1.0
17 – <18	−0.1	7.9	87.7	1.6	88.1	1.8	−5.9	2.2	0.3	0.9

A summary table of the mean values and SD of various limb deformity parameters based on a full-length standing radiograph of the unaffected lower extremity.
Data are presented as mean and SD.
MAD: positive value, medial; negative value, lateral.
JLCA: positive value, medial; negative value, lateral.

less than or equal to 1 degree each for LDFA(m), MPTA, TFA, and JLCA ($P > 0.05$).

Fifty-two of the 253 children had multiple radiographs over time. Using repeated-measures analysis of variance, the values of various deformity parameters of these 52 children obtained at different ages were compared with the results of the cross-sectional study of the subgroup of patients at that age. The results demonstrated no differences in mean MAD ($P = 0.95$), LDFA(m) ($P = 0.57$), MPTA ($P = 0.95$), TFA ($P = 0.88$), and JLCA ($P = 0.99$) between the 2 sets of radiographs.

DISCUSSION

Angular deformities of the lower extremities in children are commonly encountered in clinical practice. The perceived lower limb malalignment can be either physiological or secondary to a variety of congenital and acquired etiologies. Based on a landmark study of radiographs of children from birth to 16 years, Salenius and Vankka[2] determined the progressive changes in the TFA with age. They reported pronounced varus TFA at birth with progressive change to valgus alignment by 3 years in most children. However, their findings were based on a limited radiograph of the knee and tibia that was likely done supine. Details of the radiographic technique and patient positioning were not mentioned, and a published radiograph of a 14-month-old child showed complete overlap of the proximal fibula by the adjacent tibial metaphyses, indicating external rotation of the knee.[9] Moreover, only the TFA was measured, with no details of the MAD or the contribution of the orientation of the distal femur and proximal tibia to the changes in lower limb alignment over time. When examining the frontal plane of the lower extremity with full-length standing radiographs, besides assessing the MAD, one can measure the joint orientation angles of the femur (LDFA) and tibia (MPTA) as well as the angulation between the articular surfaces of the distal femur and proximal tibia (JLCA). Such comprehensive analysis of lower limb deformities has clinical relevance. For instance, in a child with genu varum, in addition to a proximal tibial deformity, there may be a substantial varus malorientation of the distal femur and laxity of the lateral collateral ligament contributing to the medial MAD. If the medial MAD in such a patient is fully corrected with a single proximal tibial osteotomy, the resultant knee joint obliquity with persistent malorientation and ligamentous laxity can result in abnormal translational and shear forces at the knee joint, which

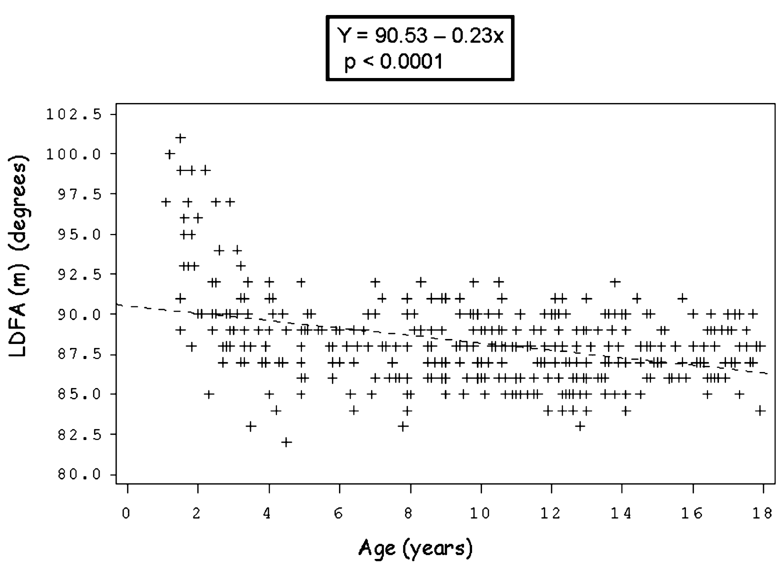

FIGURE 2. A scatter plot of the regression analysis demonstrating the relationship between the child's age and the LDFA(m).

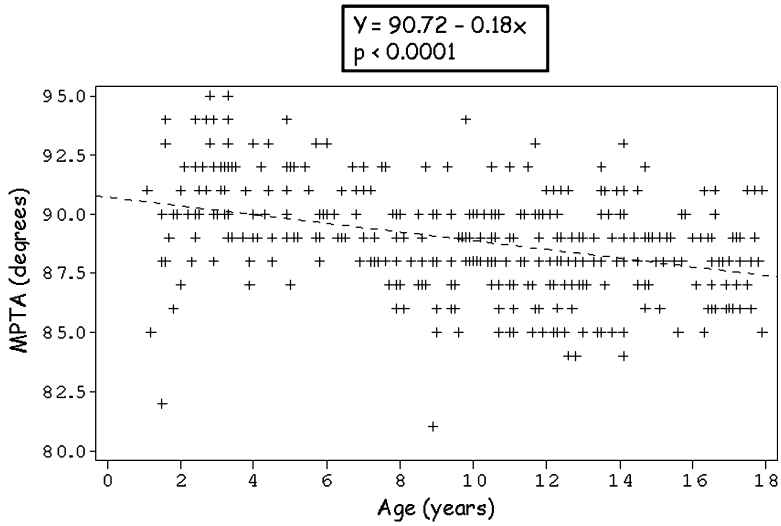

FIGURE 3. A scatter plot of the regression analysis demonstrating the relationship between the child's age and the MPTA.

may be a precursor to premature osteoarthritis. Based on the full-length standing radiographs of adult subjects, several authors have reported the reference values of various frontal plane alignment measures and joint orientation angles with very similar findings.[3,5–7] The average value for MAD is 10 mm medial (mean ± 1 SD, 3–17 mm medial), LDFA(m) 88 degrees (mean ± 1 SD, 85–90 degrees), MPTA 87 degrees (mean ± 1 SD, 85–90 degrees), and JLCA 2 degrees medial inclination (mean ± 1 SD, 1–3 degrees medial).[3] However, using parameters derived from the adult population as the target alignment and orientation of the lower limb for young children may further contribute to a suboptimal outcome.

A full-length standing AP radiograph of the entire lower limb, centered at the knee, allows for a comprehensive analysis of the magnitude and source of limb malalignment[3] as well as an assessment of limb length discrepancy.[4] This radiographic technique is reproducible[12,13] and is more accurate than clinical methods for assessing frontal plane deformities of the lower limb.[14] However, standardization of technique for obtaining a standing radiograph of the lower extremities and precise patient positioning can be challenging in a young child. In addition, prevalence of internal tibial torsion and lack of ossification of the patella in early childhood can further compromise the accuracy of information obtained from such a radiograph. Several authors[7,9,15–18] have studied the effect of lower limb rotation on radiographic assessment of frontal plane alignment and noted overestimation of varus alignment with external rotation of the extremity. Stricker and Faustgen[9] reviewed standing radiographs of children with bowlegs and found a 7-degree difference in TFA with 30 degrees of external rotation. They suggested that an overlap of the proximal fibular metaphyseal shadow on the proximal tibia of less than 60% was a useful guide for judging neutral rotation of the lower limb in young children. Thus, to avoid measurement errors related to patient positioning, in the current study, we maintained the *patella forward* position of the knee by using a standardized radiographic technique and excluding any images with greater than 60% overlap of the proximal tibiofibular joint.

Various genetic, humoral, and biomechanical factors likely control physeal growth and development of lower limb alignment.[19–21] Frost[20,21] popularized the concept of a "chondral growth force response curve." He elaborated on the effect of increasing amounts of compressive loads at the physis on longitudinal bone growth in children. Based on his observations, between zero load and a certain threshold, increasing compressive load stimulates growth. Further increase in compressive load beyond a certain point can inhibit growth, and large enough compressive loads can entirely stop further growth.[20,21] This hypothesis is supported by certain clinical observations. For instance, in severely obese children with genu varum because of Blount disease, the excessive compressive forces can cause relative growth inhibition medially, with progressive increase in varus malalignment.[22] On the other hand, mild genu varum as normally seen in infancy may lead to differential growth of the distal femur with growth stimulation medially and thus help restore normal knee alignment. This paradigm of biomechanical control of knee alignment may explain our observation of gradually decreasing LDFA with progressive change from varus to valgus orientation of the distal femur from the age of 1 to 4 years. Once the MAD was within 4 mm of the midpoint of the knee joint, no substantial progressive changes in MAD or the orientation of the distal femur and proximal tibia were noted. MacMahon et al[23] likened the change from genu varum to genu valgum to neutral alignment of the knee over the first few years of childhood to the swing of a pendulum that equalizes vertical growth about the knee. They suggested that not only differential growth of the physes but also remodeling of the cancellous metaphyseal bone of the distal femur and proximal tibia responds to changing combinations of compressive and bending stresses until equilibrium is attained by the age of 5 years.

To our knowledge, the current study is the first report on the reference values of frontal plane alignment and joint orientation parameters that is based on full-length standing radiographs of the lower extremities in the pediatric population. A summary of our results is presented in table form and may be useful to the clinician (Table 7). Due to ethical concerns with conducting a prospective study of radiographs in otherwise asymptomatic children, we performed a retrospective review of the unaffected extremity in young patients who had a standing full-length radiograph for a variety of reasons. We did use stringent inclusion and exclusion criteria and used a standardized radiographic and measurement technique that was highly reproducible. Since we were unable to find any differences of greater than 1 degree based on sex, side, and underlying etiology, we feel that there were no substantial differences in the various deformity parameters within our patient population.

Besides observing the shift from varus to valgus alignment of the lower limb in the second year of life, we were also able to quantify the MAD noted in normal limbs of children. We observed that the initial medial axis deviation of the lower extremity was primarily related to the varus orientation of the distal femur. The distal femoral varus orientation, indicated by a mechanical lateral distal femoral angle of greater than 90 degrees, gradually approached the adult value of 88 degrees by the age of 4 years. The JLCA between the distal femur and proximal tibia had a lateral apex until the age of 4 years, likely related to the varus orientation of the distal femur and physiological laxity of the knee joint. As the knee alignment and distal femoral varus changed toward neutral, the joint line convergence transitioned to apex medial after the age of 4 years. Furthermore, after the age of 7 years, all radiographic parameters of joint orientation around the knee were within the range of reference values that are reported for adults.[3] Despite changes in limb alignment with age, at no time did the mechanical axis of the extremity fall beyond the central half of the knee joint, that is, throughout childhood, the mechanical axis station remained between −1 and +1.

Because we used a standing radiograph to assess lower limb alignment, we were unable to study the frontal plane deformity parameters for infants younger than 1 year. However, our findings of changes in lower limb alignment after the age of 1 year are in agreement with the transitions noted by others using clinical examination[1] and limited radiographs of the lower extremity.[2] We did find variability in the values for the frontal plane deformity parameters among the children that was similar in magnitude to the variations noted in the adult studies.[3] Nevertheless, it would be prudent to await the results of a larger, possibly multicenter study, assessing different patient populations before these references values can be applied universally.

In summary, in our study population of children aged between 1 and 18 years, the change in alignment of the lower limb between the ages of 1 and 4 years from varus to valgus was primarily related to progressive decrease in varus orientation of the distal femur. By the age of 7 years, all joint orientation angles were noted to be within the reference values available for the adult population. Thus, in children older than 7 years, one may use available adult values[3] when assessing lower limb alignment using a full-length standing radiograph. However, in children younger than 7 years old, the clinician should use age-specific values for limb alignment and joint orientation of the lower extremity. Thus, by appropriately customizing treatment, surgeons can avoid iatrogenic deformities and further improve outcome after surgical reconstruction and limb realignment in the skeletally immature patient population.

REFERENCES

1. Heath CH, Staheli LT. Normal limits of knee angle in white children-genu varum and genu valgum. *J Pediatr Orthop*. 1993;13:259–262.
2. Salenius P, Vankka E. The development of the tibiofemoral angle in children. *J Bone Joint Surg Am*. 1975;57:259–261.
3. Paley D. *Principles of Deformity Correction*. Berlin, Germany: Springer; 2002.
4. Sabharwal S, Zhao C, McKeon JJ, et al. Computed radiographic measurement of limb-length discrepancy. Full-length standing anteroposterior radiograph compared with scanogram. *J Bone Joint Surg Am*. 2006;88:2243–2251.
5. Cooke TD, Li J, Scudamore RA. Radiographic assessment of bony contributions to knee deformity. *Orthop Clin North Am*. 1994;25: 387–393.
6. Hsu RW, Himeno S, Coventry MB, et al. Normal axial alignment of the lower extremity and load-bearing distribution at the knee. *Clin Orthop Relat Res*. 1990;255:215–227.
7. Moreland JR, Bassett LW, Hanker GJ. Radiographic analysis of the axial alignment of the lower extremity. *J Bone Joint Surg Am*. 1987;69:745–749.
8. Sabharwal S, Badarudeen S, McClemens E, et al. The effect of circular external fixation on limb alignment. *J Pediatr Orthop*. 2008; 28:314–319.
9. Stricker SJ, Faustgen JP. Radiographic measurement of bowleg deformity: variability due to method and limb rotation. *J Pediatr Orthop*. 1994;14:147–151.
10. Mielke CH, Stevens PM. Hemiepiphyseal stapling for knee deformities in children younger than 10 years: a preliminary report. *J Pediatr Orthop*. 1996;16:423–429.
11. Winer BJ. *Statistical Principles in Experimental Design*. 2nd ed. New York, NY: McGraw Hill; 1971:283–293.
12. Feldman DS, Henderson ER, Levine HB, et al. Interobserver and intraobserver reliability in lower-limb deformity correction measurements. *J Pediatr Orthop*. 2007;27:204–208.
13. Odenbring S, Berggren AM, Peil L. Roentgenographic assessment of the hip-knee-ankle axis in medial gonarthrosis. A study of reproducibility. *Clin Orthop Relat Res*. 1993;289:195–196.
14. Hinman RS, May RL, Crossley KM. Is there an alternative to the full-leg radiograph for determining knee joint alignment in osteoarthritis? *Arthritis Rheum*. 2006;55:306–313.
15. Hunt MA, Fowler PJ, Birmingham TB, et al. Foot rotational effects on radiographic measures of lower limb alignment. *Can J Surg*. 2006;49:401–406.
16. Jiang CC, Insall JN. Effect of rotation on the axial alignment of the femur. Pitfalls in the use of femoral intramedullary guides in total knee arthroplasty. *Clin Orthop Relat Res*. 1989;248:50–56.
17. Koshino T, Takeyama M, Jiang LS, et al. Underestimation of varus angulation in knees with flexion deformity. *Knee*. 2002;9:275–279.
18. Lonner JH, Laird MT, Stuchin SA. Effect of rotation and knee flexion on radiographic alignment in total knee arthroplasties. *Clin Orthop Relat Res*. 1996;331:102–106.
19. Ballock RT, O'Keefe RJ. The biology of the growth plate. *J Bone Joint Surg Am*. 2003;85:715–726.
20. Frost HM, Schonau E. On longitudinal bone growth, short stature, and related matters: insights about cartilage physiology from the Utah paradigm. *J Pediatr Endocrinol Metab*. 2001;14:481–496.
21. Frost HM. Biomechanical control of knee alignment: some insights from a new paradigm. *Clin Orthop Relat Res*. 1997;335:335–342.
22. Sabharwal S, Zhao C, McClemens E. Correlation of body mass index and radiographic deformities in children with Blount disease. *J Bone Joint Surg Am*. 2007;89:1275–1283.
23. MacMahon EB, Carmines DV, Irani RN. Physiologic bowing in children: an analysis of the pendulum mechanism. *J Pediatr Orthop B*. 1995;4:100–105.