# Developmental patterns in lower-extremity length discrepancies

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## This information is current as of February 2, 2007

# Developmental Patterns in Lower-Extremity Length Discrepancies*

BY FREDERIC SHAPIRO, M.D.†, BOSTON, MASSACHUSETTS

*From the Department of Orthopaedic Surgery, Harvard Medical School,
Children's Hospital Medical Center, Boston*

ABSTRACT: A review of lower-extremity length-discrepancy data in 803 patients demonstrated that not all discrepancies continue to increase at a constant rate with time. A classification of the developmental discrepancy patterns identified is presented: type I, upward slope; type II, upward slope-deceleration; type III, upward slope-plateau (type IIIA, downward slope-plateau; type IIIB, plateau); type IV, upward slope-plateau-upward slope; and type V, upward slope-plateau-downward slope. The patterns are dependent on the nature of the conditions causing the discrepancies and on the place and time of their occurrence. The distribution of the types of patterns in the various etiological groups is presented.

The classification of developmental patterns illustrates the varying directional changes that can occur in these discrepancies and their dependence on underlying biological phenomena. Determination of the distribution of pattern types in the various conditions aids in planning the frequency of length-discrepancy studies. The patterns alone do not provide projections of final discrepancies, but when used in conjunction with the femoral-tibial length and growth-remaining charts of Green and Anderson they permit accurate projections of discrepancy to be made.

Lower-extremity length discrepancies‡ are a common

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* Read in part at the Annual Meeting of The American Academy of Orthopaedic Surgeons, Las Vegas, Nevada, February 26, 1981.

† Department of Orthopaedic Surgery, Children's Hospital Medical Center, 300 Longwood Avenue, Boston, Massachusetts 02115.

‡ The term leg-length discrepancy, which has been used commonly, is anatomically inaccurate, as *leg* refers to the region between the knee and the ankle. The entire region from the pelvis distally is the lower extremity[11] or lower limb[19], and the term lower-extremity length discrepancy is favored, although the term lower limb-length discrepancy[13] is also correct.

consequence of many congenital and acquired musculoskeletal affections of childhood[10,12,18,21,29,30,37,39,48,49,51,57,61]. The discrepancies that develop in children are susceptible to considerable change with time, as the active physes have the potential for increasing the discrepancy or correcting it, either spontaneously or after surgery. It is important to realize that not all length discrepancies increase continually with time. This review of lower-extremity length discrepancies in 803 children who were followed to skeletal maturity demonstrated that several patterns of developmental discrepancy occur. These are dependent on the nature of the conditions causing the discrepancies and on the place and time of their occurrence; they do not refer to changes following bone surgery. This paper describes the classification of patterns of developmental discrepancy that has evolved and demonstrates its use in conjunction with the Children's Hospital Medical Center femoral and tibial length charts[5] and femoral and tibial growth-remaining[4] charts in the management program for lower-extremity length discrepancies[44].

## Materials and Methods

The longitudinal data on lower-extremity length discrepancy from patients who had been followed in the Growth Study Unit at the Children's Hospital Medical Center, Boston, over a forty-year period (1940 to 1980) were carefully studied. The patterns of developmental discrepancy that developed were demonstrated by charting the extent of a discrepancy directly against time as represented by the patient's chronological age. The patterns were also related to skeletal age to show their independence from that parameter. Lower-extremity length discrepancies were documented by standard techniques using teleoradiographs for the patients who were younger than five years old. Orthoradiographs, from which femoral and

tibial measurements were made, were used for all of the older patients[24]. Skeletal age was determined from posteroanterior radiographs of the left wrist and hand. These radiographs were correlated with the Todd atlas[58] until 1950 and with the Greulich and Pyle atlas[26] thereafter.

For inclusion in this review, an individual had to have been followed by radiographic means at the Growth Study Unit for a minimum of five years (or from the onset of disease), either to the time of skeletal maturity or to the time of bone surgery. Owing to the deep interest of Dr. William T. Green and his staff, virtually all of the patients in the series were assessed annually, and often semi-annually, from the time of onset or detection of the disease to maturity. It must be emphasized that these patients were followed *prospectively* because they had an affection in which lower-extremity length discrepancy was known to occur, rather than being seen only after a clinically apparent discrepancy had developed. With the exception of the group of patients with a fractured femoral diaphysis, the patients included in this review had to have had a discrepancy of 1.5 centimeters or more at some time during the period of assessment. The classification does not refer to any change in discrepancy that followed surgical physeal arrest, diaphyseal lengthening, or osteotomy.

The disease entities that were studied and the number of patients in each group were as follows. There were eighteen patients with proximal femoral focal deficiency, 102 with congenital coxa vara and a congenitally short femur (some with associated anomalies of the leg and foot), seventeen with Ollier's disease (enchondromatosis), twenty-one with physeal destruction, 115 with poliomyelitis, thirty-three with septic arthritis of the hip, 116 with a fractured femoral diaphysis, twenty-nine with a hemangioma, seventeen with neurofibromatosis, forty-six with hemiparetic cerebral palsy, 113 with hemiatrophy or hemihypertrophy (anisomelia), thirty-six with juvenile rheumatoid arthritis, and 140 with Legg-Perthes disease. The distribution of pattern types, the average discrepancy in centimeters, and the range of discrepancies before surgery were assessed for each group.

## Results:
### Classification of Developmental Patterns in Lower-Extremity Length Discrepancies

The classification is illustrated in Figure 1.

*Type I, upward slope pattern:* The lower-extremity length discrepancy develops and increases continually with time, at the same proportionate rate.

*Type II, upward slope-deceleration pattern:* The lower-extremity length discrepancy increases at a constant rate for a variable period of time, and then shows a diminishing rate of increase independent of skeletal maturation.

*Type III, upward slope-plateau pattern:* The discrepancy first increases with time, but then stabilizes and remains unchanged throughout the remaining period of growth.

*Type IIIA, downward slope-plateau pattern:* The discrepancy decreases with time, but then stabilizes and remains unchanged throughout the period of growth.

*Type IIIB, plateau pattern:* The discrepancy, detected initially after it has developed, remains unchanged throughout the remaining period of growth.

*Type IV, upward slope-plateau-upward slope pattern:* The discrepancy first increases, then stabilizes for a variable but considerable period of time, and then increases again toward the end of the growth period.

*Type V, upward slope-plateau-downward slope pattern:* The discrepancy increases with time, stabilizes, and then decreases in the absence of surgery.
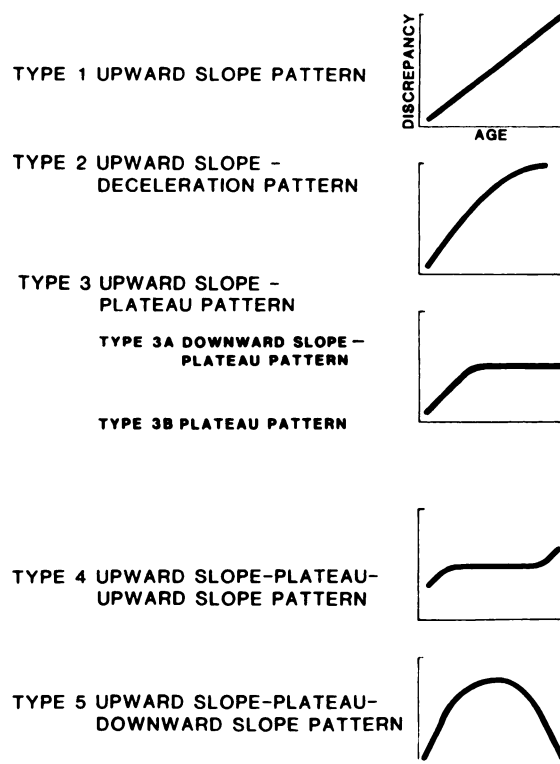


TYPE 1 UPWARD SLOPE PATTERN

TYPE 2 UPWARD SLOPE - DECELERATION PATTERN

TYPE 3 UPWARD SLOPE - PLATEAU PATTERN

TYPE 3A DOWNWARD SLOPE - PLATEAU PATTERN

TYPE 3B PLATEAU PATTERN

TYPE 4 UPWARD SLOPE-PLATEAU- UPWARD SLOPE PATTERN

TYPE 5 UPWARD SLOPE-PLATEAU- DOWNWARD SLOPE PATTERN

FIG. 1

The classification of the developmental patterns.

## Illustrative Case Reports
### Type I, Upward Slope Pattern

*Mild discrepancy* (Fig. 2): At the age of one year and seven months, a healthy boy was noted to have a 2.1-centimeter shortening of the right lower extremity. Neurological and musculoskeletal assessment was otherwise normal and there was no history of trauma, infection, or synovial irritation. Radiographs of the spine and lower extremities showed no bone anomaly other than the length discrepancy. The discrepancy gradually increased, with the femoral and tibial rate of inhibition from the chronological ages of one year to eleven years being 6.84 per cent. A left distal femoral arrest was performed at the skeletal age of twelve years and six months. The diagnosis was hemiatrophy (anisomelia).

*Moderate discrepancy* (Fig. 3): A girl had poliomyelitis affecting the right lower extremity at the age of one year and eight months. At the chronological age of ten years and two months, there was a 6.9-centimeter discrepancy caused by growth inhibition. From the
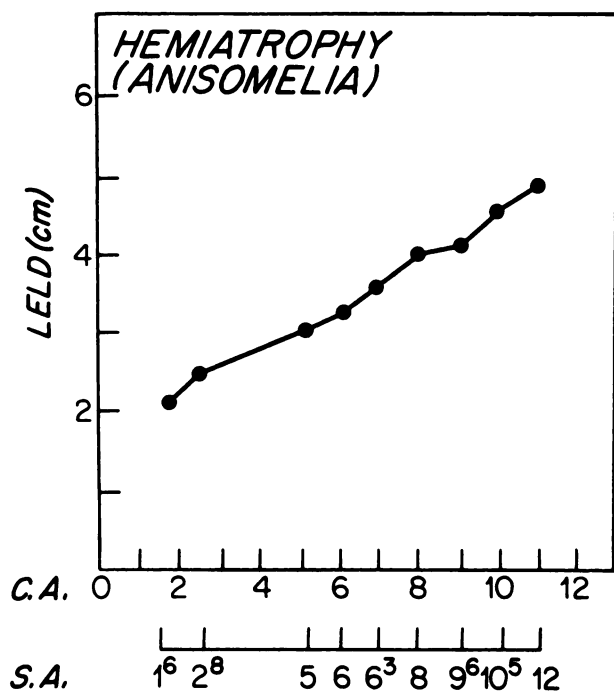
FIG. 2

The type-I pattern in a patient with hemiatrophy (anisomelia).

chronological ages of one year and nine months to ten years and two months, the femoral and tibial rate of inhibition was 22.97 per cent. Physeal arrest of the distal end of the femur and the proximal ends of the tibia and fibula on the left reduced the discrepancy to 0.6 centimeter at maturity.

*Severe discrepancy* (Fig. 4): A girl was noted to have a markedly shortened and deformed right lower extremity shortly after birth. At the age of one year and ten months, there was no development of the right
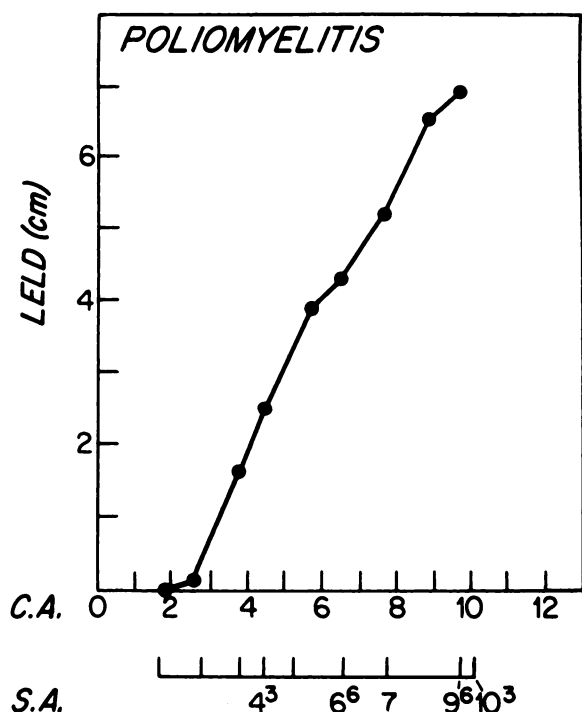


FIG. 3

The type-I pattern in a patient with poliomyelitis.

acetabulum and no bone outline of the proximal third of the right femur. The diagnosis was proximal femoral focal deficiency, type D. Sequential teleoradiographs and orthoradiographs showed severe and progressive shortening with time. The initial radiographic measurement at the age of three years and six months indicated that there was 11.0 centimeters of shortening from the iliac crest to the distal end of the tibia. This progressed to a shortening of 28.8 centimeters at the chronological age of thirteen years.

### Type II, Upward Slope-Deceleration Pattern

A one year and six-month-old girl had poliomyelitis affecting the right lower extremity (Fig. 5). A teleoradiograph made nine months after the onset of the disease showed 0.4 centimeter of shortening of the right lower limb. The discrepancy increased at a regular and fairly rapid rate from the age of two years and three months until she was eight years and
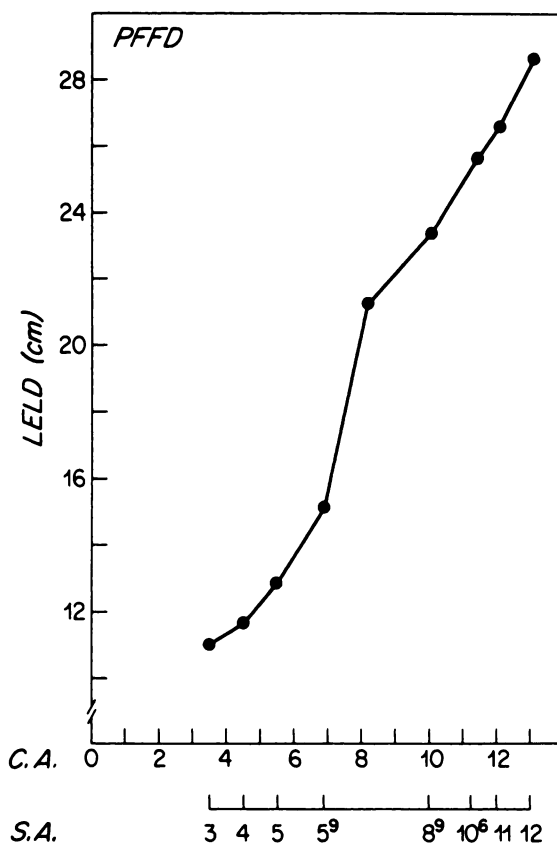


FIG. 4

The type-I pattern in a patient with proximal femoral focal deficiency.

ten months old, at which time it measured 3.9 centimeters. The rate of increase then slowed dramatically, and over the next three years and eight months the discrepancy increased only 0.4 centimeter, to 4.3 centimeters. During this time the child's skeletal age increased by four years and three months. Between the ages of two years and three months and seven years and one month, the growth of the right femur was 86 per cent that of the left; from the ages of seven years and one month to twelve years and six months, it was 95 per cent that of the left; and from ten years to twelve years and six months, it was 98 per cent that of the left. Distal femoral physeal arrest at the age of twelve years and seven months (skeletal age, eleven years and six months) resulted in equal limb lengths at maturity.

In another case, a girl was noted from birth to have an enlarged right lower extremity (Fig. 6). Due to considerable hypertrophy of the soft tissues and an increase in the length of the extremity, a diagnosis of hypertrophy associated with multiple subcutaneous hemangiomas was made. When she was one year and nine months old, radiographic studies indi-
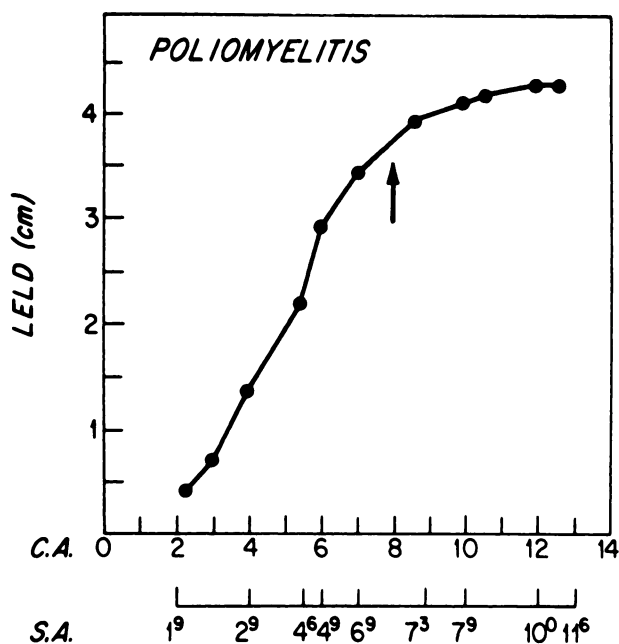
FIG. 5

The type-II pattern in a patient with poliomyelitis.

cated a 2.4-centimeter shortening of the left lower extremity. The discrepancy continued to increase at a continuous rate with time, and at the age of seven years 4.9 centimeters of shortening was documented by orthoradiographs. Over the next several years the discrepancy continued to increase, but at a much slower rate. Soft-tissue surgery was not done and no radiotherapy was given. Between the chronological ages of four years and six months and seven years, the shorter, normal left lower limb demonstrated 90 per cent of the growth of the longer, abnormal right limb. Over the next five and one-half years, however, from the age of
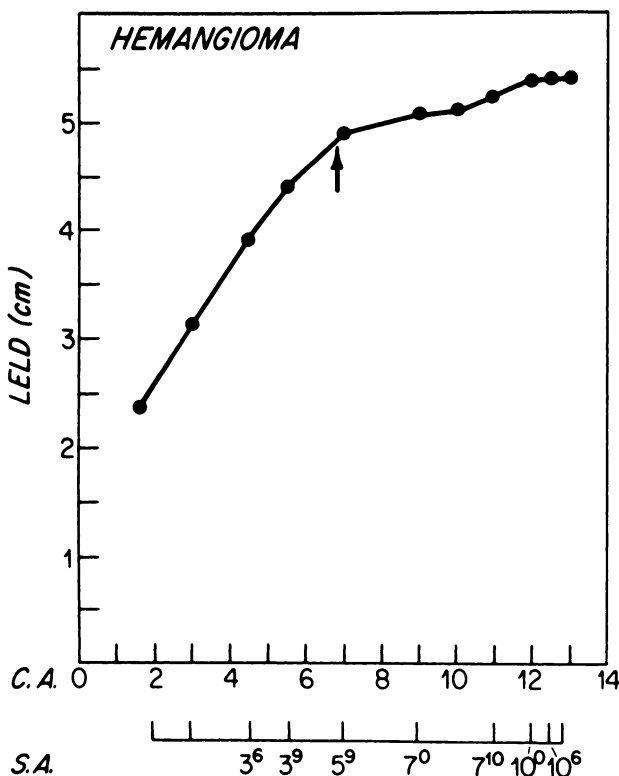


FIG. 6

The type-II pattern in a patient with multiple soft-tissue hemangiomas.

seven years to twelve years and eight months, the short limb grew almost as much as the involved limb, resulting in a 97 per cent increase in length compared with the longer side. Stapling of the distal femoral physis and proximal fibular and tibial physes on the right at the chronological age of twelve years and six months resulted in a decrease of the discrepancy from 5.4 centimeters to 1.1 centimeters of left lower-extremity shortening at skeletal maturity.

### Type III, Upward Slope-Plateau Pattern

A three year and six-month-old boy sustained a fracture of the middle of the right femoral shaft (Fig. 7). This was treated by traction with a Kirschner wire in the distal end of the femur for three and one-half weeks, followed by several weeks in a hip spica. The fracture was allowed to consolidate at anatomical length rather than with the now generally accepted 1.5 centimeters of overlap. Three months after the injury, 0.4 centimeter of shortening on the left was documented by orthoradiographs. Due to overgrowth of the right femur, the discrepancy increased to 1.7 centimeters of shortening on the left by two years after fracture. The discrepancy then persisted unchanged until the age of fifteen, at which time a right distal femoral physeal arrest was performed. At skeletal maturity, the right lower extremity measured 0.2 centimeter longer than the left one.

A four year and eight-month-old girl had juvenile rheumatoid arthritis of the right knee (Fig. 8). Four months after the onset of the disease, orthoradiographs documented a 0.2-centimeter limb-length discrepancy, the left lower extremity being shorter. The discrepancy had increased to 1.4 centimeters by the age of seven, but then persisted virtually unchanged as the disease remained quiescent. At the age of fourteen years and one month there was a 1.7-centimeter discrepancy.

### Type IIIA, Downward Slope-Plateau Pattern

When a femoral shaft fracture in a child heals with shortening, the overgrowth phenomenon decreases the discrepancy. When the overgrowth has terminated, any remaining discrepancy persists unchanged, on a plateau.

### Type IIIB, Plateau Pattern

Occasionally patients are seen after a discrepancy has occurred, but documentation has begun in the stable phase and the difference remains unchanged.

### Type IV, Upward Slope-Plateau-Upward Slope Pattern

This boy had a severe *Staphylococcus aureus* septic arthritis of the left hip when he was nine months old (Fig. 9). Incision, drainage, and marsupialization of the capsule was done several hours after aspiration, and antibiotic therapy was begun. Radiographic assessment two months later showed that the left lower extremity was 0.2 centimeter shorter than the right one. At the age of two years the discrepancy was 0.7 centimeter, which it remained for several years, being 0.8 centimeter at the age of thirteen years. Premature closure of the involved femoral capital physis then occurred, and the discrepancy increased a further 0.9 centimeter in one and one-half years. Coxa vara developed due to the continued growth of the greater trochanteric epiphysis. A right distal femoral physeal arrest was performed at the skeletal age of fourteen years and six months in an attempt to achieve limb-length equality.

### Type V, Upward Slope-Plateau-Downward Slope Pattern

Legg-Perthes disease was diagnosed on the right in a boy at the age of five years and two months (Fig. 10). He was otherwise healthy and remained so during the entire course of his growth period. He was treated with a patten-bottom abduction brace for four years. Spontaneous resolution from 1.9 to 0.2 centimeter of shortening of the right lower extremity occurred in association with healing of the femoral head and discontinuation of bracing.

A girl, five years and two months old, had juvenile rheumatoid arthritis involving the right knee (Fig. 11). The initial growth study documented a 1.2-centimeter length discrepancy, the left side being short. The discrepancy increased to 2.4 centimeters, but then spontaneously diminished over the next five years to 1.4 centimeters at maturity.

The distribution of developmental patterns that was documented in the various diseases is listed in Table I. The average maximum discrepancy that was reached during the period of assessment before bone surgery and the range of maximum discrepancies in patients with the various diseases before bone surgery are listed in Table II.

## Developmental Patterns in Specific Disease Entities

*Proximal femoral focal deficiency:* In each of the eighteen patients with this condition, severe progressive shortening of the type-I pattern occurred. In types A and B, proximal femoral focal deficiency as defined by Aitken[2], the proximal part of the femur is intrinsically maldeveloped, with no effective capability for normal reconstitution even though the acetabulum and femoral head are present. In types C and D the proximal structures are even
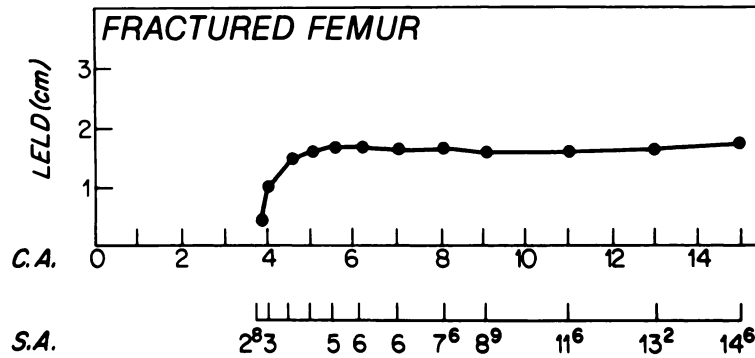


FIG. 7

The type-III pattern in a patient with a fractured femoral diaphysis.
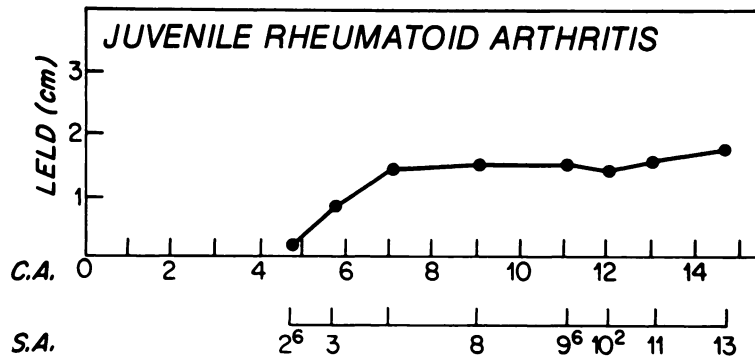


FIG. 8

The type-III pattern in a patient with juvenile rheumatoid arthritis.
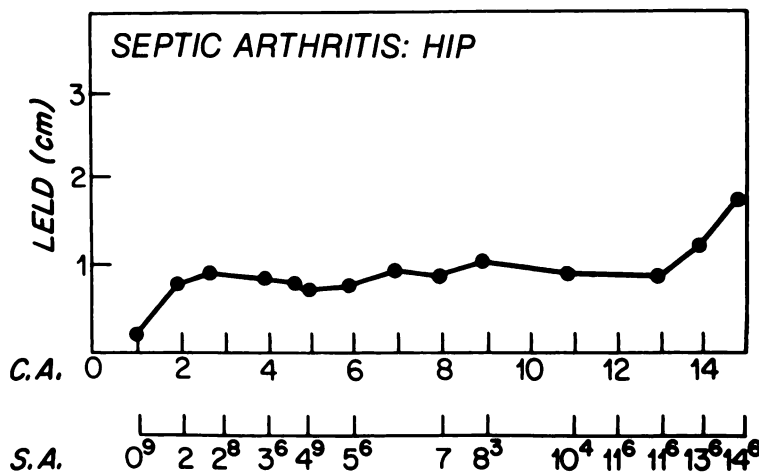


FIG. 9

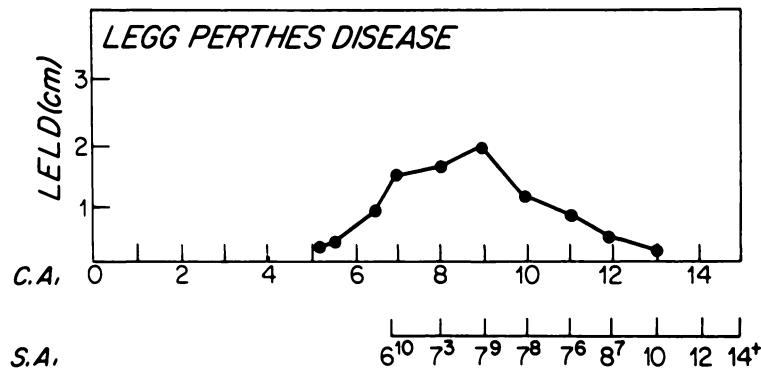The type-IV pattern in a patient with septic arthritis of the hip.

FIG. 10

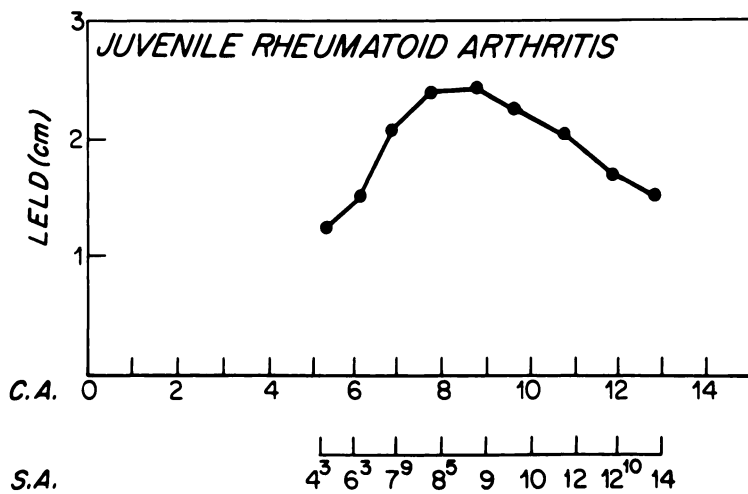The type-V pattern in a patient with Legg-Perthes disease.



FIG. 11

The type-V pattern in a patient with juvenile rheumatoid arthritis.

more markedly abnormal, with no visible ossified head and the tapered diaphysis displaced proximal to the shallow, often unrecognizable acetabulum. Proximal femoral focal deficiency in this series resulted in an average of twenty-seven centimeters of shortening, with some lower limbs showing as much as a forty-five-centimeter discrepancy. The range of femoral shortening averaged 60 per cent (range, 40 to 80 per cent) compared with the normal side. In patients classified as having type A, B, or C deficiency, the shortening averaged 57 per cent, and in type D it averaged 80 per cent. Tibial shortening averaged 7.6 per cent (range, zero to 37 per cent) and fibular shortening averaged 28 per cent (range, zero to 100 per cent) in all types. This condition caused the most severe discrepancies seen in this series and presents an extremely difficult management problem[2,8]. Accurate prediction of the final discrepancy is possible from the early years of life in patients with this condition, however, owing to the invariable type-I pattern.

Congenitally short femur including congenital coxa vara: This group was composed of patients with congenital femoral anomalies[3], including congenital coxa vara[6,63], a congenitally short femur with coxa vara, and a congenitally short femur with lateral bowing and sclerosis but

without coxa vara[42]. Many of these patients also had associated mild or moderate anomalies of the pelvis, tibia, fibula, and foot. Excluded from this group were the patients with proximal femoral focal deficiency and those with a normally shaped and only mildly shortened femur, who were categorized as having hemiatrophy (anisomelia). The average preoperative limb-length discrepancy in this group was 5.92 centimeters (range, 2.2 to 15.6 centimeters). It is important that thirty-seven of these patients showed a type-II or type-III developmental pattern. If a discrepancy reached six centimeters, it generally persisted with a type-I pattern. Those patients, however, in whom the discrepancy was less great often had a type-II or type-III pattern. Ring[42] stated that patients with a congenitally short femur (with lateral bowing, cortical sclerosis, and external rotation, but without coxa vara) continue to have an increase in the discrepancy at a regular rate with time, but the findings in the present series dispute Ring's claim.

Ollier's disease (enchondromatosis): The seventeen patients with this intrinsic bone disease demonstrated a type-I pattern. As varus or valgus femoral and tibial deformities were often associated with the shortening[45], corrective osteotomy was done frequently and length-discrepancy data that were unsuilied by any bone-surgery

TABLE I

DISTRIBUTION OF DEVELOPMENTAL PATTERNS IN THE VARIOUS DISEASES IN EIGHT HUNDRED AND THREE PATIENTS

| Condition | No. of Patients | Pattern Type | | | | |
|---|---|---|---|---|---|---|
| | | I | II | III | IV | V |
| Proximal femoral focal deficiency | 18 | 18 | 0 | 0 | 0 | 0 |
| Congenitally short femur, including congenital coxa vara (with some associated leg and foot anomalies) | 102 | 65 | 29 | 8 | 0 | 0 |
| Ollier's disease | 17 | 17 | 0 | 0 | 0 | 0 |
| Destroyed epiphyseal growth plates | 21 | 21 | 0 | 0 | 0 | 0 |
| Poliomyelitis | 115 | 64 | 25 | 17 | 9 | 0 |
| Septic arthritis (hip) | 33 | 14 | 4 | 12 | 3 | 0 |
| Fractured femoral shaft | 116 | 0 | 8 | 108* | 0 | 0 |
| Cerebral palsy (hemiparetic) | 46 | 15 | 5 | 24† | 0 | 2 |
| Anisomelia | | | | | | |
|   Hemihypertrophy | 86 | 48 | 20 | 18 | 0 | 0 |
|   Hemiatrophy | 27 | 17 | 4 | 6 | 0 | 0 |
| Hemangiomas | 29 | 9 | 8 | 10 | 1 | 1 |
| Neurofibromatosis | 17 | 11 | 2 | 3 | 0 | 1 |
| Juvenile rheumatoid arthritis | 36 | 7 | 0 | 16 | 0 | 13 |
| Legg-Perthes disease | 140 | 21 | 8 | 52 | 10 | 49 |

\* Both type-III and type-IIIA discrepancies.

† Many of these discrepancies were detected in the plateau phase (type IIIB).

intervention throughout the growth period were rare. Relentless shortening was demonstrated, however. One patient with severe involvement who was followed to skeletal maturity, with no surgical intervention, had a type-I profile, with a 35.7-centimeter discrepancy and no decline in the rate of increase. In all patients the extent of shortening paralleled the extent of radiographic involvement. The average shortening prior to physeal arrest or diaphyseal lengthening was 9.79 centimeters. Enchondromatosis was the second most serious condition causing extensive discrepancies, being exceeded only by proximal femoral focal deficiency.

*Destroyed physes:* If destruction and premature fusion of a physis occurred, a type-I pattern of discrepancy development invariably followed except at the hip (as will be described), with no tendency to compensation by the other physes in the involved bone. Such destruction is common with certain physeal fractures, such as Salter-Harris type-IV and type-V fractures[43], and often with severe type-II and type-III fractures of the distal femoral physis[34]. Other causative factors are physeal ablation during tumor resection and severe osteomyelitis, particularly in the pre-antibiotic era. Wilson and McKeever[62] documented shortening in eighteen (21.1 per cent) of eighty-five infected bones whose physes were damaged from an adjacent focus of osteomyelitis.

*Poliomyelitis:* In patients with poliomyelitis involving the lower extremity, the type-I pattern was seen com-

TABLE II

EXTENT OF LOWER-EXTREMITY LENGTH DISCREPANCIES IN THE VARIOUS DISEASES

| | No. of Patients | Maximum Discrepancy Preop. *(cm)* | |
|---|---|---|---|
| | | Average | Range |
| Proximal femoral focal deficiency | 18 | 26.79 | 13.00-44.90 |
| Congenitally short femur, including congenital coxa vara (with some associated leg and foot anomalies) | 102 | 5.92 | 2.20-15.60 |
| Ollier's disease | 17 | 9.79 | 4.00-35.70 |
| Poliomyelitis | 115 | 3.33 | 1.50-6.20 |
| Cerebral palsy (hemiparetic) | 46 | 2.00 | 1.50-3.20 |
| Hemihypertrophy | 86 | 3.18 | 1.60-6.90 |
| Hemiatrophy | 27 | 3.07 | 1.50-4.90 |
| Hemangiomas | 28 | 3.09 | 1.80-5.60 |
| Neurofibromatosis | 21 | 4.40 | 2.00-8.80 |
| Juvenile rheumatoid arthritis | 36 | 2.26 | 1.50-5.90 |
| Legg-Perthes disease (maximum femoral-tibial discrepancy) | 140 | 2.14 | 1.50-4.90 |

monly. There was, however, a distinct tendency for the discrepancy to increase most rapidly in the first four or five years following infection, with the rate of increase diminishing after that (types II and III). This fact has been pointed out previously by Green and Anderson[21], Ratliff[40], and White[61], and is documented in Figure 5. Assessment of the 115 patients who were followed for ten years or more, either to the time of skeletal maturation or, in most instances, to the time of surgical physeal arrest, indicated that almost one-third of the patients demonstrated a type-II or type-III pattern. It has been theorized that improved function due to tendon transfers and bracing is responsible for the lessening rate of discrepancy with time[61]. Detailed studies during the poliomyelitis era[56] described a good but variable correlation between the extent of shortening and the severity of involvement. No correlation between the age at onset and amount of shortening was found in one major study[56], although this finding was challenged[56].

*Septic arthritis of the hip:* Damage to the femoral capital physis in septic arthritis can produce serious growth discrepancies[16]. In this series such discrepancies tended to increase with time, but a type-I pattern was seen only in 42 per cent of the patients, and most commonly when the infection had occurred relatively late, after the age of seven or eight years. An assessment of pattern development in this group was obscured somewhat more often than in other groups because of the necessity for early and often for frequent surgical intervention, although femoral osteotomy *per se* was done only infrequently in growing children. The patterns in this assessment were based on femoral and tibial lengths. In following such patients, however, it is important to be aware that if dislocation occurs, the practical consideration in discrepancy relates to the distance between the iliac crest and the floor. This can be documented accurately by orthoradiographs, but a combination of measured blocks under the shortened extremity in association with a standing anteroposterior radiograph of the pelvis is also important, especially if only scanograms have been used to document the discrepancy.

Even with complete destruction of the physis, however, femoral shortening did not invariably become worse with time, particularly in the younger patients. When the greater trochanter overtakes the involved femoral head in height, the femur resumes a somewhat more regular growth pattern[60] as the greater trochanter and distal femoral physes are normal, thus accounting for the type-II and III patterns that were seen. The growth of the proximal end of the femur, in particular the relationship between the capital femoral and the greater trochanteric epiphyses, has been discussed in relation to normal, diseased, and experimental situations[36,52]. The complexities of this particular growth area must be understood in order to plan the proper time for surgical intervention[17].

The type-IV growth pattern was limited almost exclusively to abnormalities of the proximal end of the femur such as occur with septic arthritis of the hip, osteomyelitis of the femoral neck, Legg-Perthes disease, and avascular necrosis of the femoral head complicating treatment of congenital dislocation of the hip. In patients in whom damage was relatively mild, premature fusion of the proximal femoral capital physis has been noted years after the infectious insult. The premature fusion can be detected two or three years prior to skeletal maturation by the progressive change in the relationship of the level of the greater trochanteric physis to that of the proximal femoral capital physis. It is, therefore, extremely important to continue periodic assessment of these children by monitoring carefully the relationship of the head and neck to the greater trochanter until skeletal maturity, even if the discrepancy has been in a plateau phase for several years. Although the average increase in the late phase was only approximately one centimeter, this amount often converted a clinically insignificant discrepancy to one of 2.4 centimeters or more, and thus warrants special consideration.

*Fractured femoral diaphysis:* The stimulation of femoral growth after a diaphyseal fracture in children who are two to eleven years old has been well documented[7,9,14,27,46]. It is an obligate phenomenon and occurs regardless of whether a fracture has healed with an overlap, end to end, or in a lengthened position, or whether it occurred in the proximal, middle, or distal third of the femur[46]. The average femoral overgrowth from the time of fracture-healing in this series was 0.92 centimeter (range, 0.4 to 1.8 centimeters). Ipsilateral tibial overgrowth, averaging 0.3 centimeter, was also documented. Seventy-eight per cent of the overgrowth had occurred by fifteen months after injury. In 85 per cent of the patients, the overgrowth had terminated at an average of three years and six months after fracture. The overgrowth phenomenon manifested itself as the type-III slope-plateau pattern in 108 (93 per cent) of the patients, with the limb-length discrepancy remaining unchanged throughout the remainder of growth. If a fracture heals at length or with lengthening, the overgrowth produces an upward slope-plateau pattern. If a fracture heals with shortening, the overgrowth diminishes the discrepancy such that, in terms of this classification, it is a downward slope-plateau representation. A type-II pattern occurred in eight patients whose fractures had healed with excessive angulation. In these, continuing overgrowth presumably occurred due to the prolonged remodeling process.

Tibial overgrowth following tibial fracture has been reported as being most marked in patients who are less than nine years old[25]. In an isolated tibial fracture, overgrowth rarely is severe enough to require continuing long-term length assessment, but it can be troublesome when there is an associated ipsilateral femoral fracture.

*Osteomyelitis:* Overgrowth of a long bone that is the site of osteomyelitis has also been known to occur[39,50,54,59,62], although such cases were not studied in this series. In Wilson and McKeever's series[62], eighteen

(21.2 per cent) of eighty-five patients had overgrowth of the involved bone. This occurred almost always when the osteomyelitis was diaphyseal and damage to the physis had not occurred. Trueta[59] stated that overgrowth following osteomyelitis lasts until medullary recanalization occurs (a type-III pattern in this classification), by which time the sequestra would have been resorbed and a more normal vascular pattern would have been established. The maximum overgrowth was 2.0 centimeters, but most patients had only a few millimeters. In chronic recurrent osteomyelitis of childhood, however, overgrowth will persist.

*Hemiparetic cerebral palsy:* Most of these patients have a lower-extremity length discrepancy with the shortening on the involved side. In this series, type-I and type-III developmental patterns predominated. As has been reported previously, lower-extremity shortening in hemiplegic children occurred almost exclusively in the tibia[55]. We have found that lower-extremity length discrepancy represents an important consideration in many hemiparetic patients. Of the forty-six patients who were followed in the Growth Study Unit for five years or more, and who had a discrepancy of more than 1.5 centimeters, the average discrepancy just prior to physeal arrest or at maturity was 2.0 centimeters (range, 1.5 to 3.2 centimeters). It is important to note, however, that physician referral strongly influenced our study of this disease entity, unlike other diseases for which the condition itself was reason for referral. The majority of patients with cerebral palsy in our hospital were not assessed for discrepancies. Femoral-tibial shortening alone does not give a true measurement of the functional discrepancy that may be present in the limb, as subtle dynamic or static hip and knee-flexion contractures and an expected, but rarely documented, shortness in the height of the foot may further decrease the functioning length of the hemiparetic limb. If a tendo achillis lengthening is done and the lower-extremity length discrepancy is not appreciated, there may be a tendency for equinus deformity to recur on a mechanical compensatory basis.

*Anisomelia (hemihypertrophy and hemiatrophy):* This group of patients is discussed together even though two different diagnoses, hemihypertrophy and hemiatrophy, were made. As this paper reviews the cases of patients who were assessed over a forty-year period, it was frequently not clear what criteria were used to include a patient under each particular designation, but the diagnosis of hemihypertrophy does not include patients who were noted to have hemangiomas, lymphangiomas, lipomatosis, or neurofibromatosis. At present the diagnosis of hemiatrophy is applied to patients in whom both limbs individually appear to be normal, with the shorter limb diagnosed as being hemiatrophic. The developmental patterns in both groups were similar, however, and for the purposes of this classification the entity is referred to as anisomelia. Most of these patients (57 per cent) demonstrated a type-I pattern, with the remainder equally divided between type

II and type III. The average maximum discrepancy in these 113 patients was 3.16 centimeters (range, 1.5 to 6.90 centimeters).

*Hemangiomas:* As used for a diagnostic category in this series, hemangiomas encompassed a wide histopathological variety of vascular anomalies, including capillary hemangioma (port-wine stain), cavernous hemangioma, arteriovenous aneurysms and fistulae, congenital varicosities, and mixed lymphangioma-hemangioma lesions[32,33]. Ipsilateral overgrowth occurred in twenty-nine (83 per cent) of thirty-five patients, while in the remainder the limb was shorter on the ipsilateral side. Nine (31 per cent) of the twenty-nine patients who showed overgrowth had the type-I pattern, the remainder being type II or III. Involution is a well known occurrence in some types of hemangiomas and may account for slowing of growth stimulation[32,33]. Although there were well documented instances in our series when partial resection of the soft-tissue lesions also diminished the growth stimulation, many patients demonstrated a type-II or type-III pattern in the absence of any surgery. The average discrepancy prior to bone surgery in this group of patients was 3.09 centimeters (range, 1.8 to 5.60 centimeters). The developmental pattern in this group must be observed carefully in the middle years of the first decade of life, as considerable discrepancy may develop and projections that are based on the expectation of the same rate of growth stimulation can be misleading.

*Neurofibromatosis:* Growth stimulation was documented on the involved side in the seventeen patients who did not have a tibial pseudarthrosis[1]. Prior to physeal arrest, the average discrepancy was 4.40 centimeters (range, 2.0 to 8.8 centimeters). Shortening was also associated with neurofibromatosis in the six patients in whom a pseudarthrosis occurred. The type-I pattern was commonest, although type-II, type-III, and type-V patterns were seen also. As surgical intervention in an attempt to establish union was so frequent in the patients with pseudarthrosis, the natural length-discrepancy patterns were not available for assessment.

*Juvenile rheumatoid arthritis:* In patients with monoarticular or pauciarticular juvenile rheumatoid arthritis, variable developmental patterns occurred. Types I, II, III, and V were all seen. The knee is the commonest area of involvement in juvenile rheumatoid arthritis and involvement there is most likely to result in clinically significant discrepancy[53]. The type-I pattern was seen most frequently in patients whose initial attack of rheumatoid arthritis occurred after the age of nine years. In these patients a type-I pattern developed due to the relatively rapid, premature physeal fusion of the bones comprising the involved joint. The type-II and type-III patterns were seen most often in patients whose initial synovitis, occurring in the first few years of life, resulted in physeal stimulation and overgrowth. In our series, once the synovitis had resolved, physeal growth altered toward a more normal rate and the discrepancy either persisted unchanged or

increased at a much slower rate. The type-V pattern resulted from a slowing of physeal stimulation over a few years prior to plate closure. Whether the type-V pattern was due to decreased use or to an alteration in the timing mechanism for closure due to disease, or to both, is uncertain, but the phenomenon itself was well documented. It was not possible to predict which patients would have a type-II, III, or V pattern. Similar overgrowth can occur following such inflammatory conditions about the knee in childhood as tuberculosis[39], septic arthritis[50], and hemophilia[57]. Indeed, in what appears to represent a description of a type-V pattern, Phemister[39] quoted Bergmann as observing "equalization of length years after overgrowth produced by tuberculosis of the knee beginning in early childhood".

*Legg-Perthes disease:* In the 140 patients with a lower-extremity length discrepancy associated with unilateral Legg-Perthes disease, the involved side was always shorter at some time during the period of assessment[47]. All five types of discrepancy pattern were seen. Femoral shortening occurs due to cessation of growth during the phase of necrosis of the secondary ossification center, due to subchondral collapse with the coxa plana deformity, and due to disuse in association with therapy, and it has long been recognized as part of the disease entity[31]. The femoral shortening was frequently associated with shortening of the ipsilateral tibia due to decreased use of the limb with unilateral brace therapy. Once bracing was discontinued, the tibial discrepancy decreased. Twenty-one patients demonstrated a type-I pattern; eight, a type-II; fifty-two, a type-III; ten, a type-IV; and forty-nine, a type-V pattern. When only the femoral lengths were assessed, fourteen patients (10 per cent) demonstrated a type-IV pattern. The occurrence of the type-IV pattern was analogous to that seen in some patients with septic arthritis of the hip with only mild destruction. Premature fusion of the capital femoral epiphyseal growth plate occurred, with a late alteration of the femoral head-greater trochanter relationship. It is probable that the type-IV pattern would have been seen more often, but the performance of distal femoral epiphyseal arrests in these patients made it difficult to document the type-IV change. There was a good correlation between the age of the patient at onset of the disease and the final discrepancy pattern[47]. The average age at onset in the patients who showed the type-I pattern was 8.7 years, for type II it was 6.5 years, for type IV it was 5.6 years, and for type V it was 5.3 years. These numbers reflect the better healing that occurs in younger patients with Legg-Perthes disease, who have a longer time available for the slow repair process.

## Discussion

Several systems for predicting limb-length discrepancy have been presented over the past several decades. Accurate knowledge of the amount of growth remaining in femoral and tibial physes at any particular age became of practical importance after Phemister[39] demonstrated the relative ease and value of arresting physeal growth in the longer bone. Hatcher[12,20] developed a formula for determining the amount of growth remaining in the distal end of the femur and proximal end of the tibia. Although the figures were based on averages at chronological age periods, they provided the first quantitative information on expected growth increments[12]. White[61] timed all epiphyseal arrests on the basis that the distal end of the femur grew 9.5 millimeters per year and the proximal ends of the tibia and fibula grew 6.4 millimeters per year. Gill and Abbott[18] improved the accuracy of growth projections greatly by using percentile height tables and determinations of skeletal age. Their method took the individual's relative growth and maturation rate into consideration rather than using average values, as had been done previously, although the limb lengths were based on percentage determinations from data for total height. Anderson et al. documented the actual femoral and tibial lengths[5] radiographically in a large number of boys and girls and plotted the data in percentile standard-deviation charts. They also provided femoral and tibial growth-remaining charts[4] based on radiographic studies. Moseley, using the Green-Anderson data, developed a straight-line graph for leg-length discrepancies by converting the normal growth curve for logarithmic methods into a straight line[38].

It has been recognized for some time that the length parameter of *normal* growth can be represented accurately by logarithmic plotting[28,41]. It is incorrect, however, to assume that pathological processes are as readily predictable by logarithmic plotting or any other formula. The straight-line graph or the growth-inhibition method[23] might well lead to inaccurate projections, particularly if the assessments stop too early in patients with conditions in which type-II, late plateau type-III, type-IV, or type-V patterns may be evolving. The types of patterns that occur in each disease category have been delineated. When more than one pattern is seen, clinical and radiographic information will help to anticipate which discrepancy pattern or patterns will develop. Thus, knowledge of the developmental pattern classification, the natural and specific history of the condition causing a particular discrepancy, and the pattern type or types that occur in the condition allow the physician to project the ultimate extent of the discrepancy with clinically acceptable accuracy. The frequency with which clinical and radiographic evaluations of the discrepancy should be done must strike a balance. The evaluations should not be terminated too early or done too infrequently on the expectation that straight-line graph or growth-inhibition projections always will suffice, and on the other hand they should not be done unnecessarily often, as though the eventual outcome were totally in doubt. The developmental patterns themselves cannot be used to make accurate mathematical projections, since growth, particularly during growth-spurt periods and immediately prior to skeletal maturity, is not linear with time. The patterns do, however, permit accurate projections of discrepancy to be made using the femoral and tibial length charts[5]

and the femoral and tibial growth-remaining charts[44], which do take the non-linearity of growth into consideration.

The length and growth-remaining charts were developed from information obtained by making yearly orthoradiographs of sixty-seven boys and sixty-seven girls between the ages of one and eighteen years; they give the most accurate indication of individual bone lengths that currently is available[5]. Their value lies in indicating the lengths of the femur and tibia and the growth remaining in those bones in relation to the standard deviation position. Smooth curves of growth are shown, with the individual growth spurt that occurs between the ages of ten and fourteen blurred by averaged data. When an individual child's growth is plotted, the growth spurt will often change the standard deviation position of the limb lengths. If maturation is relatively early the limb length will be on a higher percentile; if maturation is late the limb length will be on a relatively lower percentile. Awareness of this factor is important in determining the amount of growth remaining in a bone and in projecting its final normal length. Growth is generally linear between the ages of four and ten years[18,35], and if a child is on the first standard deviation above the mean at the age of seven, it is very likely that at skeletal maturity limb length will also rest along that percentile. Thus, length data obtained before the adolescent growth spurt are of great value in indicating what the child's projected mature level will be. If information is available only from the period between ten and fourteen years, however, awareness of the relationship of skeletal age to chronological age is important. If the skeletal age is retarded or advanced by six months or more in relation to chronological age, the correct growth percentile can best be determined by plotting the femoral and tibial lengths in relation to skeletal age, not chronological age[18,22,23].

The assessment of skeletal age[23] is important in using the Green-Anderson Children's Hospital Medical Center method. While a wide variation in skeletal-age reading can be demonstrated among readers who do it infrequently, the assessments become highly reproducible when done by readers who do many. In the Growth Study Unit the skeletal-age readings were always done by one or two people to provide a consistent standard. Although the Greulich and Pyle atlas[26] has certain limitations, responsible physicians must remain aware that even if they do not pay attention to the rate of skeletal maturation, the skeleton does.

Management of the growing patient with a limb-length discrepancy can be improved by knowledge of the classification of developmental patterns; the type or types of patterns that can occur with the particular disease process; radiographic documentation of the lengths of the lower extremities; a chart of the relationship between discrepancy and age, to outline the developmental pattern that is evolving; the percentile standing of the normal limb and the abnormal limb; and the patient's skeletal age.

A brief discussion of the use of the developmental pattern classification follows.

### Type I

The type-I discrepancy increases at a constant rate with time, as the rate of inhibition (or stimulation) remains uniform throughout the growth period. In essence, if one is certain that a type-I pattern will evolve then one radiographic assessment of length, especially after the age of two years, will suffice for accurate determination of the final discrepancy (although more determinations are always performed). In the first two years of life there can be considerable shifting of length between various percentiles[35], whereas afterward the distinct tendency is for normal growth to persist along the same percentile. For example, if at the age of four years the involved femur in a child with proximal femoral focal deficiency is 63 per cent as long as the normal femur, one can project the final discrepancy by determining the percentile on which the normal femur lies from the femoral and tibial length chart and noting the femoral length at maturity for the percentile. Sixty-three per cent of the value represents the projected final length of the involved femur, and the difference between the two lengths represents the projected femoral length discrepancy.

The growth-remaining charts[4] are particularly useful when the type-I pattern is due to physeal destruction. The femoral and tibial growth-remaining data can be localized accurately to the involved physis, and the values for the distal end of the femur and proximal end of the tibia can be read directly from the chart. If the proximal femoral physis has closed, the projected growth loss is determined on the basis that 30 per cent of the growth of the femur occurs at the proximal physis and 70 per cent occurs at the distal physis[15]. Thus, by multiplying the value for remaining distal femoral growth by three-sevenths, the value for the remaining proximal femoral growth is obtained. If the distal tibial plate has fused, projected growth loss is 45/55 of the proximal tibial growth-remaining value. The amount of growth remaining is determined from the line that corresponds to the standard deviation position of the normal bone on the femoral and tibial length charts[5].

### Type II

This is the most difficult pattern to project because the discrepancy shows a decremental rate of increase which varies from patient to patient and from condition to condition. The information available from the period of constant increase has no predictive value, as the discrepancy values themselves cannot "be aware" that a change in discrepancy pattern is about to occur. This group therefore requires especially careful monitoring. For example, at the age of eleven, a child's femoral discrepancy measures 5.0 centimeters. Length on the short side is 87 per cent of normal. The growth percentile on which the normal femur lies allows one to project its final length. The growth rate in the most recent six-month period indicates that the short femur has shown 93 per cent growth in relation to the nor-

mal side, thus demonstrating the deceleration in the development of discrepancy. The growth remaining in the normal femur is 8.6 centimeters, as indicated by the femoral and tibial length chart and the growth-remaining chart (taking a distal femoral value of 6.0, multiplying this by three-sevenths [2.6] to give the proximal femoral value, and adding the two together). A projection of the change in discrepancy with time indicates that growth on the shorter side, based on the recent six-month deceleration, would be at least 93 per cent of 8.6 centimeters, such that the discrepancy would increase only by 7 per cent of 8.6 centimeters, or 0.6 centimeter, yielding a final maximum projection of 5.6 centimeters of discrepancy. If there is more time before surgical intervention, a further six-month growth assessment might allow for an additional calculation. By this time, projections that allow for a clinically acceptable result (discrepancy of less than 1.0 centimeter) can be made.

## Type III

Once a plateau has been reached, the lower-extremity length discrepancy will not change throughout the remaining period of growth. The prototypical type-III pattern is seen with overgrowth following fracture of a femoral diaphysis. The timing for the corrective physeal arrest is arrived at by using the femoral and tibial length charts and the femoral and tibial growth-remaining charts. The final discrepancy is known once the plateau phenomenon has been documented to have occurred, as neither further stimulation nor inhibition will occur.

## Type IV

Type-IV discrepancies characteristically are seen after hip diseases in childhood that affect the proximal femoral capital epiphysis, such as septic arthritis of the hip with mild-to-moderate damage, Legg-Perthes disease, and avascular necrosis of the femoral head in association with treatment of congenital dysplasia of the hip. Premature closure of the proximal femoral capital epiphysis can occur after the discrepancy has remained in a plateau phase for as long as a decade. Radiographic indication of premature

fusion of the proximal femoral capital epiphysis is demonstrated by a change in the relationship of the femoral head to the greater trochanter due to relative overgrowth of the latter. The growth discrepancy to be expected from premature fusion, once it has occurred, is obtained by determining the growth remaining in the distal end of the femur, multiplying that value by three-sevenths (to give the amount of overgrowth expected from the proximal end of a normal femur), and, since growth is *not* occurring, adding this value to the pre-existing discrepancy to give the projected final discrepancy.

## Type V

If a discrepancy is beginning to correct itself, the growth charts are referred to, to see how much growth remains. A determination can then be made as to whether the spontaneous correction will be insufficient, will result in equal limb lengths, or might result in overcorrection.

The developmental pattern classification provides a visual representation of the varying directional changes that can occur with time in lower-extremity length discrepancies (Fig. 1). The dependence of the patterns on the causes of the discrepancies and on the time and anatomical locations of their occurrence is stressed. The demonstrated relationships between the pattern type and the particular disease entity (Table I) should aid in planning the nature and frequency of assessments of discrepancy. In those conditions in which several pattern types occur, the classification serves mainly to point out that variability. Some of the contributing factors to the various patterns within each disease entity have been assessed further[46,47,53]. The patterns *alone* do not provide for an accurate projection of a final discrepancy (except in type III), as growth, particularly during the adolescent growth spurt and immediately prior to skeletal maturity, is not linear with time. The patterns do, however, permit accurate projections of discrepancy to be made using the femoral-tibial length and growth-remaining charts of Anderson et al.[4,5].

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