Current Issues
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Growth in Pediatric Orthopaedics

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The mature musculoskeletal system is the end result of a highly ordered, coordinated sequence of cellular and extracellular matrix events initiated early in embryonic life and continued to skeletal maturity. These events include transformation of undifferentiated mesenchymal tissue into bone, cartilage, synovium, tendon, ligaments, and muscle, and integration of these tissues to form the musculoskeletal system (7).

Growth is a consequence of microgrowth at the cellular level in the growth plate. Although the histologic structure is the same, each physis has its own characteristics and dynamics. The study of growth as height, weight, and body proportions considers macrogrowth, the culmination of the effects of microgrowth of various body segments and the total individual. One must not lose sight of other aspects of growth, such as the impact of the nervous system. Growth assessment provides a reference for the orthopaedist for normal development and, in abnormal states, a guideline for treatment (13,14).

Growth is a volumetric revolution. From birth onwards, height increases 350% and weight, 20-fold. Growth involves changes in proportion. At birth, the lower limbs make up 30% of the standing height in contrast to 48% at skeletal maturity. The infant head makes up 25% of the standing height and only 13% at skeletal maturity. Growth reflects a succession of accelerations and decelerations. Because growth does not occur simultaneously in the same magnitude or rate in varied body segments, it is synchronized to maintain limb and spine relationships (20,34–36). A change in direction of parameters that alters synchronization with other parameters may signal an abnormality, a return to normal, or the onset of a normal phase of growth. For this reason, a sequence of measurements of the important parameters is far superior to a single measurement. Simple measurement tools are required at the time of evaluation: height gauge, weight scales, measuring tape, and bone age atlas. Ten simple questions will guide the orthopaedist to the information that is required.

How tall is the child?
What is their sitting height?
What is their subischial leg length?
What are their chronological and bone ages?
What is their annual growth?
What is the growth remaining in the trunk and lower limbs?
Where is the child in their normal development?
Where is the child on their pubertal path?
Are the proportions of the child normal?
What is the child’s weight?

BIOMETRIC MEASUREMENTS

Limited growth data is obtained from a single measurement. Birthdays are a convenient reminder for annual longitudinal growth evaluations. In some cases, evaluating the child every 6 months allows easy assessment of growth velocity of the child and different body segments. These measurements provide a real-time image of growth and generate charts that make decisions easier. An excellent example of this is growth velocity, because it provides the best indicator of the beginning of puberty onset upon which so many decisions rest. The first pubertal skeletal sign is an increase in height of more than 0.5 cm per month or 6 cm a year.

Standing height
In children less than 5 years of age, it is recommended that height be measured with the child supine because in this age group, it is easier and more reliable.

Between birth and maturity, the body will grow approximately 1.2 to 1.3 m. At 5 years of age, standing height is 60% of the adult height, reaching 80% of the final height by the age of 9. Arm span is an indirect way to evaluate standing height. Excellent correlation exists between arm span and the standing height (9,21). In 77% of normal children, arm span is less than 5 cm of the standing height; in 22% of healthy children, arm span is between 5 and 10 cm; and in 1%, it is greater than 10 cm.

Arm span is routinely used in any child who has a spine significant deformity to calculate the normal pulmonary function values. This relationship is also useful to diagnose disorders characterized by a limb-trunk disproportion, e.g., Marfan’s syndrome.
Sitting height

In children less than 2 years of age, sitting height is measured with the child supine for the same reasons that standing height is measured with the child supine in this age group. The child should always be measured under the same conditions using the same measuring instruments. Measurement of sitting height can be useful in anticipating the onset of puberty. In an average population, puberty starts at approximately 75 cm sitting height in girls and 78 cm sitting height in boys. At 84 cm of sitting height, 80% of girls have menarche.

Subischial leg length

The body segment made up by the lower extremities is known as the subischial leg length. It is measured by subtracting sitting height from standing height. At birth, subischial leg length averages 19 cm. At the completion of growth, it averages 81 cm in boys and 74.5 cm in girls. This 62 cm of growth in boys and the 55.5 cm in girls contribute a far greater percentage of growth in height than does the trunk and account for the changing body proportions during growth (Fig. 1).

Intrauterine development

By the time of birth, the infant’s weight is 6 million times that of the original egg. Length increases steadily and rapidly during the first 6 months in utero; weight gain is the most rapid during the final 3 months of gestation. At the end of the second trimester of gestation, the fetus has reached 70% of its final predelivery length, measuring 30 cm, but it has achieved no more than 20% of birth weight. During the third trimester, the fetus gains weight at the highest rate (700 g per month).

Birth to 5 years

After birth, not only does the overall rate of growth vary at different ages, the rate at which various segments of the body grow also differs. During the first 5 years of life, sitting height and subischial length grow about the same. From age 5 years to puberty, sitting height accounts for one third of the gain, whereas subischial leg length accounts for two thirds. From puberty to maturity, the ratio is reversed.

Standing neonate height is 30% of the final height at maturity. By the age of 5 years, the standing height has doubled and is 60% of the final height. Height gain in the first year is as great as it is during the entire growth surge during puberty. At the age of 1 year, growth rate slows, with the child growing 10 cm between the ages of 1 and 2 years and 7 cm between the ages of 3 and 4 years. At birth, sitting height is approximately 66% of the final sitting height with an additional 30 cm to grow. Growth in the subischial leg length follows a pattern almost identical to that for sitting height. At birth, the lower limbs are relatively small compared with the trunk. By the age of 5 years, subischial leg length has increased to more than 50% of the final length.

From 5 years to 10 years

Between 5 and 10 years of age, there is a marked deceleration in growth, with standing height increasing approximately 5.5 cm per year. Two thirds (3.5 cm) of this growth occurs in the lower limb and one third (2 cm) in the sitting height. The trunk grows at a slower rate than the lower limbs and body proportions change.

Puberty

Beyond the age of 10 years, the growth patterns of boys and girls diverge. On average, girls experience the onset of puberty at the age of 11, boys at the age of 13. Acceleration in the velocity of growth best characterizes the onset of puberty (6,12,13). Four main characteristics dominate puberty: dramatic increase in stature; change of upper and lower body segment proportions; change in overall morphology; and sexual characteristic development. There are wide individual variations in onset and duration of puberty (36). The ultimate standing height depends on unpredictable factors: onset, tempo, and duration of puberty (9,12,17).

During puberty, standing height increases by approximately 1 cm per month. At the onset of puberty, boys have 14% (± 1%) of their remaining standing height to grow. This is approximately 22.5 cm (± 1 cm) made up of 13 cm in sitting height and 9.5 cm in subischial leg length. Girls have 12% (± 1%) of their standing height to grow. This is approximately 20.5 cm (± 1 cm) made up of 12 cm in sitting height and 8.5 cm in subischial leg length (12,34–36) (Figs. 2,3).

Growth rate peaks during puberty between 13 and 15 years of bone age in boys and 11 and 13 years of bone age in girls. By the time girls and boys pass bone ages of 13 and 15, respectively, lower limb growth comes virtually to a standstill, with all remaining growth (4.5 cm) taking place in sitting height (12,34–36). These figures, ratios, and rates provide only a partial reflection of the growth phenomena. Precise evaluation of the characteristics of puberty, using the Tanner classification, the onset of menstruation, and Risser’s sign needs to be undertaken with great care. A major problem with using the onset of menarche or Risser sign is that they occur after the pubertal growth rate has begun to slow.

![FIG. 1. Proportion in percentage of the lower limb and sitting height: at birth, standing height makes up 70% of sitting height; at skeletal maturity, 52%. Reproduced with permission from Morisson RT, Weinstein SL. Lovell and Winter’s Pediatric Orthopaedics. 5th ed. Philadelphia, PA: Lippincott Williams and Wilkins, 2001.](image-url)

Secondary sexual characteristics

Secondary sexual characteristics develop throughout the course of puberty. The first physical sign of puberty in boys (testicular growth in 77%) occurs on average 1.7 years before the peak height velocity and 3.5 years before attaining adult height. Bone age will be approximately 13 years at the onset of puberty. Risser sign is zero and the triradiate cartilage is open. At this age, girls have well-developed secondary sexual characteristics, and their rate of growth is decelerating. In 93% of girls, breast budding occurs about one year before peak height velocity. This averages 11 years in bone age. Risser sign is still zero and the triradiate cartilage is open at the onset of puberty. Menarche occurs approximately 2 years after breast budding and final height is usually achieved 2.5 to 3 years after menarche.

After menarche, girls gain the final 5% of their standing height, approximately 3 to 5 cm. The appearance of axillary hair, though variable, often signals the peak of the pubertal growth curve.


Pubertal diagram

Using these landmarks, it is possible to construct a diagram relating all of the events occurring during puberty. Even when one indicator is missing or does not match the other, it is still possible to have a good idea where the child is on their way through puberty.

The first phase of the pubertal growth spurt corresponds to the acceleration in the velocity of growth and is the major portion of the pubertal growth spurt. This phase lasts 2 years from approximately 11 to 13 years of bone age in girls and 13 to 15 years of bone age in boys. The gain in standing height for girls during this phase is approximately 14.5 cm, made up of 6.5 cm in sitting height and 7 cm in subischial leg length. The gain in standing height for boys during this phase is approximately 16.5 cm, made up of 8.5 cm in sitting height and 8 cm in subischial leg length.

Triradiate cartilage closure occurs approximately halfway on the ascending limb of the pubertal curve and corresponds to an approximate bone age of 12 years for girls and 14 years for boys. After closure of the triradiate cartilage, there remains a significant amount of remaining growth—greater than 12 cm of standing height for girls and more than 14 cm for boys.

The second phase of the pubertal growth spurt is a period of deceleration in the rate of growth, which lasts 2.5 years from 13 to 15.5 years of bone age in girls and from 15 to 17.5 years of bone age in boys. During this phase, boys and girls gain approximately 6 cm in standing height with 4.5 cm coming from an increase in sitting height and 1.5 cm coming from an increase in the subischial leg length. During this phase, the increase in sitting height contributes 80% of the gain in the standing height.

Menarche most often occurs when the rate of growth is slowing, usually between bone age of 13 and 13.5 years and corresponds to Risser I on the iliac apophysis. At this stage, the average girl will gain an additional 4 cm of sitting height and 0.6 cm of subischial leg length. Menarche is not a precise indicator of puberty. Forty-two percent of girls have menarche before Risser I, 31% at Risser I, 13% at Risser II, 8% at Risser III, and 5% at Risser IV.

Puberty peak

The pubertal peak is a juxtaposition of three micro-peaks (Fig. 4). The first peak is marked by lower limb growth at the very beginning of puberty; the second peak is marked by trunk growth; the third peak is marked by chest growth. The lower limb peak takes place between P1 and P2 Tanner signs for boys and Breast 1 and Breast 2 for girls. The trunk peak happens between P2 and P3 for boys and Breast 2 and Breast 3 for girls. The chest growth peak occurs on the descending side of pubertal growth.

IMAGING ASSESSMENT OF GROWTH

Accurate assessment of bone age is not easy. The younger the child, the more difficult it is to determine future growth and the more likely errors are committed (22). Children are often a bone age mosaic. Bone age determinations for the hands, elbows, pelvis, and knees do not always agree coincidentally. Bone age determination is often made too quickly and with too little information. When using a reference method (e.g., the Greulich and Pyle atlas), it is important to understand knowledge of these methods and their limitations. The bone age as determined by the method of Greulich and Pyle. There are several methods to evaluate bone age (1,17,19,31). Knowledge of these methods and their limitations is important. We compared the Greulich and Pyle atlas with its French counterpart, the Sempe atlas (31).

![Diagram of Girls' Pubertal Growth](Image)

**FIG. 5.** The pubertal growth curve in girls. The fusion of the distal phalanx of thumb occurs at the same period as elbow closure. Risser 1 occurs on the descending side about six months after elbow closure. Usually menarche occurs at this period. Tanner signs: Breast 1, Breast 2 and Breast 3 on the ascending side. Axillary hairs are poor indicators. Reproduced with permission from Morrissy RT, Weinstein SL. Lovell and Winter’s Pediatric Orthopaedics. 5th ed. Philadelphia, PA: Lippincott Williams and Wilkins, 2001.

No significant difference was seen between data in these atlases. The Tanner and Whitehouse method (36), though accurate, is very time consuming and difficult, making it impractical in daily practice. The Greulich and Pyle atlas is sufficient for clinical decision making in orthopaedic practice when used by physicians knowledgeable in this method. A weakness of the Greulich and Pyle atlas is that there are few changes in the hand during the critical time of puberty. For this reason, I find the Sauvegrain method to be of more value during puberty (30). It shows good correlation with the Greulich and Pyle atlas but is easier to use.

At the beginning of puberty, growth centers of the elbow are wide open, but 2 years later, when the peak velocity of the pubertal growth spurt is reached and growth begins to slow, they are all completely closed. This complete closure occurs 6 months before Risser I. There is great value in analysis of olecranon ossification. At the start of puberty (bone age 11 for girls and 13 for boys), two olecranon ossification centers appear. Six months later, the centers merge in a crescentic shape. By bone age 12 years for girls and 14 years for boys, the olecranon apophysis is rectangular and 6 months later, the olecranon apophysis begins to fuse with the ulna, and in another 6 months, fusion is complete (17) (Figs. 5, 6).

The Risser sign is a commonly used marker of skeletal maturation, especially in the treatment of scoliosis. The duration of excursion of Risser sign is variable and ranges from 1 to 3 years (4,11). Little and Sussman concluded that it is better to rely on chronologic age (25). I do not agree with their conclusions. The Risser sign should be augmented with the bone age as determined by the method of Greulich and Pyle.

The Risser sign is zero for the first two thirds of the pubertal growth spurt. The child is Risser 0 before the ascending limb of the growth acceleration curve and it gives little information other than to indicate that the peak of the growth velocity curve has not been reached. I recommend dividing this time characterized by Risser 0 into two periods based on the triradiate cartilage and its closure: triradiate cartilage open, triradiate cartilage closed. Six months later, fusion is complete (17) (Figs. 5, 6).

![Diagram of Boys' Pubertal Growth](Image)

**FIG. 6.** The pubertal growth curve in boys. The fusion of the distal phalanx of thumb occurs at the same period as elbow closure. Risser 1 occurs on the descending side about six months after elbow closure. Tanner signs: P1, P2, P3 occurs on the ascending side. Axillary hairs are poor indicators. Reproduced with permission from Morrissy RT, Weinstein SL. Lovell and Winter’s Pediatric Orthopaedics. 5th ed. Philadelphia, PA: Lippincott Williams and Wilkins, 2001.
GROWTH AND SCOLIOSIS

Sitting height evaluation plays an essential part in the treatment of scoliosis (13,14). Unfortunately, it is not recorded often enough. Change in sitting height always needs to be compared with angular spinal changes. Any spinal curve increasing by $1^\circ$ each month (12° per year) during the ascending phase of the pubertal peak is likely to be a progressive curve that will require treatment. Curves increasing by $0.5^\circ$ each month during this phase must be monitored closely. Curves gaining less than $0.5^\circ$ each month during this phase can be considered mild (13).

However, imprecise and approximate Risser’s sign may be, it is widely used as a deciding factor in scoliosis treatment. It can be very useful if its limitations are understood. As noted above, two thirds of the pubertal growth spurt has occurred before the appearance of Risser I (24). Bone age, growth rate, and secondary sexual characteristic onset are more reliable parameters. Risser stages must be considered as only one factor in the treatment equation (33).

The “crankshaft” effect on the spine after posterior spinal arthrodesis for scoliosis was described by Dubois-set (18) and analyzed by others (17,28,29,32). The crankshaft phenomenon occurs when there is a solid posterior arthrodesis with sufficient anterior growth remaining to produce a rotation of the spine and trunk with progression of the curve. The best method to prevent crankshaft phenomenon is to perform a perivertebral arthrodesis that eliminates all the growth plates of the vertebra (13,14). This is especially recommended when the triradiate cartilages are still open (29).

LOWER LIMB GROWTH

The lower limb grows more than the trunk (2,15). The cycle of growth in the lower limb is very predictable. There is a rapid increase in growth during the first 5 years of age, followed by a steady but slower growth from 5 years of age to the onset of the puberty. A slight growth spurt occurs during the accelerated velocity of growth at the beginning of puberty, and finally, early cessation of growth after the velocity peak. The femur grows more than the tibia with a constant relationship between the femur and the tibia throughout growth. Their proportions are set as early as age 5 years. Tibial length is 80% of femoral length. Fibular length is 98% of tibial length.

Femoral growth

The proximal femoral physis of the femur accounts for 30% of the femoral growth or approximately 10 cm. The distal and proximal femoral growth plates grow approximately 1 cm and 0.7 cm, respectively, each year. During puberty, this rate of growth increases to approximately 1.2 cm for the distal femur and 0.8 cm for the proximal femur (15).

Tibial growth

The tibial and femoral growth profiles are almost identical with rapid growth during the first 5 years of life, which then slows to approximately 1.3 cm each year until puberty, when growth increases to 1.6 cm per year. Growth of the tibia and the fibula are interdependent (15).
Knee growth

Growth around the knee is the largest growth site of all. The knee accounts for about two thirds of growth in the lower limb, 37% for the distal femoral physis and 28% for the tibia (2,15).

Foot growth

The length of the foot is relatively large during intrauterine life with relative diminution throughout growth (5). At birth, the foot is approximately 40% of its final size. The foot is the first segment of the musculoskeletal system to show pubertal growth change. The growth spurt of the foot occurs a few months before the start of puberty. The foot is also the first musculoskeletal segment that stops growing at maturity. Foot growth stops about 3 years before the end of skeletal maturation. Arthrodesis of the foot at the beginning of puberty will have no significant impact on the length of the foot. The foot represents 15% of the standing height in both girls and boys at skeletal maturity, an amount which must be taken into consideration during lower limb length assessment, especially in conditions that have foot manifestations, e.g., fibular hemimelia.

UPPER LIMB GROWTH

Upper limb growth follows the same pattern of development as the lower limb. The first 5 years are characterized by rapid growth. Between 5 years and the beginning of puberty, there is a plateau and, in the very beginning of puberty, a slight spurt in growth (12,27). The maturity gradient in the upper limbs is similar to that in the lower limbs. The hand shows its relatively slight acceleration of growth approximately 6 months before the forearm that reaches its peak growth velocity approximately 6 months before the upper arm. Proportions amongst the various bones of the upper and lower arms are established by 5 years of age. The ulna is 80% of the length of the humerus, whereas the humerus represents 70% of the length of the femur, a fact to consider during planning of lower limb equalization by femoral lengthening (23,26).

SUMMARY

Growth analysis should be dynamic and repeated at each clinic visit when indicated. Before any treatment decision, various growth parameters must be considered: growth velocity of standing height, sitting height, lower limbs and growth remaining of the different segments. Chronologic age must be compared with bone age and bone age must be reviewed in light of Tanner signs. One can define a "pubertal age," a synthesis of the clinical and radiologic ages (12,13,17). Bone age is the most im palpable and the most indiscernible parameter. In spite of its imperfection, use of bone age is inescapable. Charts and diagrams are only templates. They do not by themselves define a true age. They define trends and outline the evolution of growth. They should be taken for what they are—a convenient means to map the route to skeletal maturity. Percentages provide an extremely valuable and objective tool for evaluating residual growth, particularly with respect to the proportions between the length of various limb segments and between the limbs and the trunk. However diverse the ethnic origins and even though stature has increased in succeeding generations over the centuries, boys of all generations and ethnic backgrounds have approximately 14% of outstanding growth in standing height and 10% of length of the femur and tibia remaining at the beginning of puberty (3,12,17). The percentages, proportions, and ratios are stable. The humerus makes up about 20% of sitting height and 38% of standing height (17). Whatever the race, the lower limbs double in length at age 2 years, and there remains 50% of growth in the lower limbs at the age of 4 years (12). Despite the diversity of races, velocity of the standing height always has the same pattern. It is extremely rapid during intrauterine life, rapid during the first 5 years after birth, slows after 5 years of age, and followed by acceleration at puberty.

All the changes are gradual. Puberty is a short period of approximately 2 years with rapid growth changes. The milestones that mark the path during this period must be noted and understood by the orthopaedic surgeon. The best way to understand growth is to follow its patterns. One must embrace its rhythms and its cadences in order to control it. This is best done by perceptive, repetitive collection of measurements. The more accurate and frequent the data, the more sensitive and precise is the treatment. Rigorous analysis and flexibility in the interpretations are the keys for success.

REFERENCES