

Section 1

Orthopedic Problems

Chapter 713

Orthopedic Growth and Development

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There is a wide spectrum of normal orthopedic growth and development in children. Normal values are often defined as those that fall within 2 standard deviations of the mean value for the population, a range that accounts for approximately 95% of values. *Statistically normal* should not be confused with *ideal* in any given person's or parent's mind. Table 713.1 lists terms used to describe some common deviations from normal. Congenital anomalies can be categorized into production problems and packaging problems. Production problems include abnormalities caused by malformation, dysplasia, or disruption that will not spontaneously resolve (see Chapter 100). Packaging problems include deformations caused by mechanical causes, including in utero positioning and molding, and they usually resolve with time.

Table 713.1 Terminologies for Deviations

TERMINOLOGY	DESCRIPTION
Congenital	Anomaly that is apparent at birth
Deformation	A normally formed structure that is pushed out of shape by mechanical forces
Deformity	A body part altered in shape from normal, outside the normal range
Developmental	A deviation that occurs over time; one that might not be present or apparent at birth
Disruption	A structure undergoing normal development that stops developing or is destroyed or removed
Dysplasia	A tissue that is abnormal or wrongly constructed
Malformation	A structure that is wrongly built; failure of embryologic development or differentiation resulting in abnormal or missing structures

IN UTERO POSITIONING

In utero positioning produces temporary joint and muscle contractures and affects the torsional alignment of the long bones, particularly those of the lower extremities. Normal full-term newborns can have up to 20- to 30-degree hip and knee flexion contractures. These contractures tend to resolve by 4-6 months of age. The newborn hip externally rotates in extension up to 80-90 degrees and has limited internal rotation to approximately 0-10 degrees. The lower leg often has inward rotation (internal tibial torsion). The face may also be distorted; the spine and upper extremities are less affected by the in utero position. The effects of in utero positioning, therefore, are physiologic in origin and resolve by 3-4 months of age.

GROWTH AND DEVELOPMENT

Consideration of growth and development helps formulate treatment strategies designed to preserve or restore normal growth potential. Growth is subject to many variables, including genetics, nutrition, general health, endocrine status, mechanical forces, and physiologic age. Growth also varies between two anatomic regions and even between two bones of the same region.

Bone formation or ossification occurs in two different ways. In **endochondral ossification**, mesenchymal cells undergo chondrogenesis to form cartilage that matures to become bone. Most bones in the axial and appendicular skeleton are formed in this manner. In **intramembranous ossification**, osteoblasts are formed by direct differentiation of mesenchymal cells into bone. Flat bones of the skull and clavicle are examples of this pattern of bone formation.

CENTERS OF OSSIFICATION

At the beginning of the fetal period, the chondrocytes in the mid-shaft of the long bones form the **primary** centers of growth from which the bone eventually lengthens. **Secondary** centers of ossification appear in the chondroepiphysis and mostly appear postnatally. They direct the formation of bone throughout growth, particularly joint development. The ossification centers that are typically present at birth are the distal femur, proximal tibia, calcaneus, and talus (Fig. 713.1).

Anatomic Locations: Descriptive Terms

Typical **long bones** are divided into the physis, epiphysis, metaphysis, diaphysis, and perichondrial ring (Figs. 713.2 and 713.3). The physis is the growth plate located at the end of bone. The epiphysis is typically a secondary ossification center that contributes to joint development. The metaphysis is the bone adjacent to the physis on the side away from the joint. The diaphysis is the central part or shaft of long bones. The perichondrial ring contributes to appositional growth.

The articular cartilage also contributes to the growth of the epiphysis. The perichondrial ring, which surrounds the physes, and the perichondrium around the epiphyses and periosteum, which surrounds the metaphysis and diaphyseal regions of the bone, contribute to appositional or circumferential growth. Bones without physes (pelvis, scapulae, carpal, tarsal) grow by appositional bone growth from their surrounding perichondrium and periosteum. Other bones (metacarpals, metatarsals, phalanges, spine) grow by a combination of appositional and endochondral ossification.

Important Growth and Developmental Milestones

Table 713.2 summarizes some important musculoskeletal growth considerations.

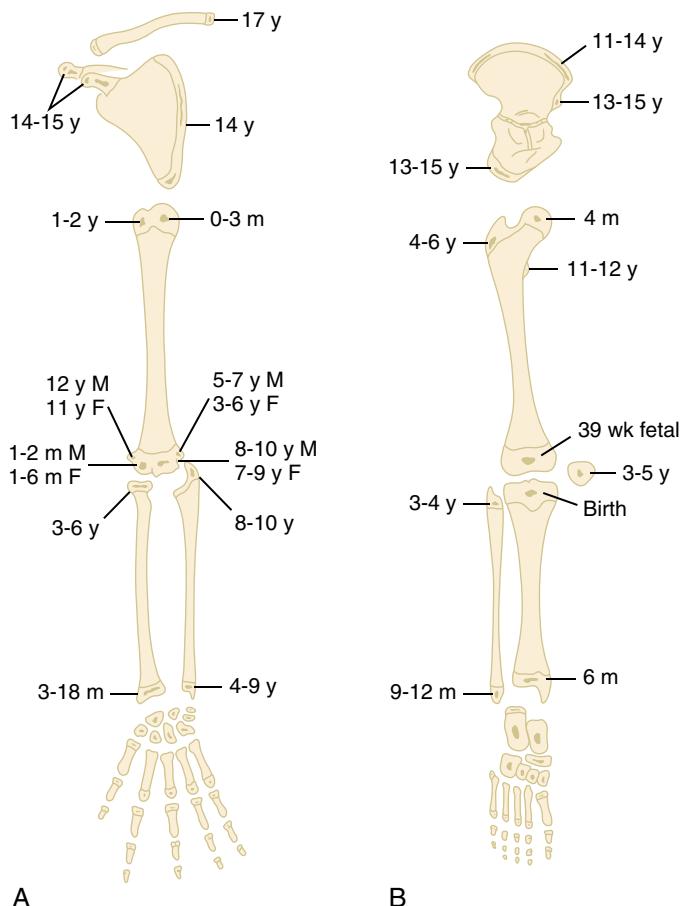


Fig. 713.1 Ages of onset of secondary (epiphyseal and apophyseal) ossification of the major bones of the upper (A) and lower (B) extremity. F, Female; M, male; m, month; wk, week; y, year. (From Caffey J. *Pediatric X-ray Diagnosis*, 8th ed. Chicago: Year Book, 1985.)

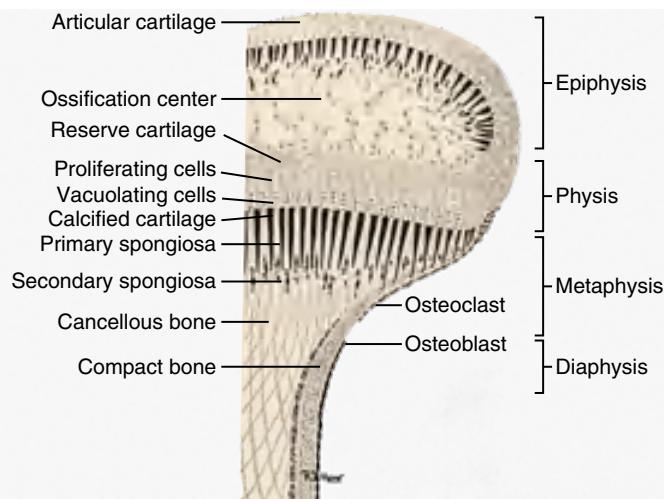


Fig. 713.3 Functional components of the growing end of a tubular bone and their anatomic substrate. (From Kan JH, Strouse PJ. *Embryology, anatomy, and normal findings*. In: Coley BD, ed. *Caffey's Pediatric Diagnostic Imaging*, 13th ed. Philadelphia: Elsevier, 2019: Fig. 128.5)

Table 713.2 Skeletal Growth Considerations

- Abnormal stature can be assessed as "proportionate" or "disproportionate" based on comparing the ratio of sitting height with sub-ischial height (lower limbs).
- Normally the arm span is almost equal to standing height.
- The head is disproportionately large at birth, and the ratio of head height to total height is approximately 1:4 at birth, which changes to 1:7.5 at skeletal maturity.
- Lower extremities account for approximately 15% of height at birth and 30% at skeletal maturity.
- The rate of height and growth increase is not constant and varies with growth spurts.
- By age 5, birth height usually doubles, and the child is approximately 60% of adult height. The child is approximately 80% of final height at 9 yr old. During puberty, the standing height increases by approximately 1 cm/mo.
- Bone age is more important than chronological age in determining future growth potential.

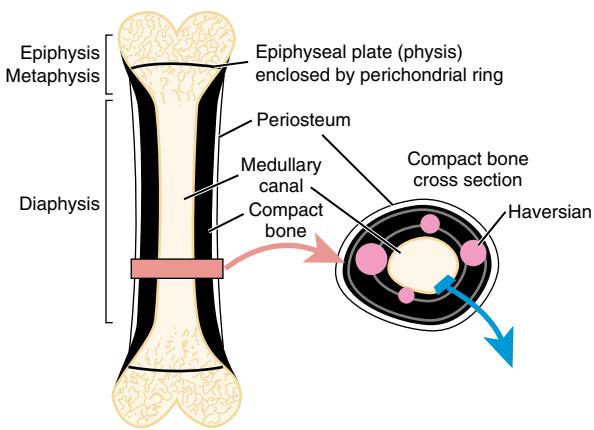


Fig. 713.2 Diagram showing typical long bone divisions.

Growth Patterns in Upper and Lower Extremities

The upper extremity grows longitudinally, primarily from physes of the proximal humeral physis and the distal radial and ulnar physes. In the lower extremity, most of the longitudinal growth occurs around the knee, in the distal femoral and the proximal tibial physes (Fig. 713.4).

In the hip joint, the acetabulum forms with the convergence of three primary ossification centers: ischium, ilium, and pubis.

GAIT/FUNCTIONAL MATURATION

Functional mobility develops in infants in a predictable fashion (Table 713.3). Failure to achieve functional milestones is an indication for referral to a neurologist to determine if a central nervous system (CNS) problem exists. CNS maturation contributes significantly to the development of gait. In early ambulation (at 8-15 months), the child usually has a wide-based gait with hyperflexion of hips and knees, and initial contact with the heel. By the age of 2 years, the wide gait diminishes, reciprocal arm swing begins, and there is increased stride length and velocity. Adult fluid gait patterns usually start developing by 3 years and mature to an adult-like pattern by age 7 years.

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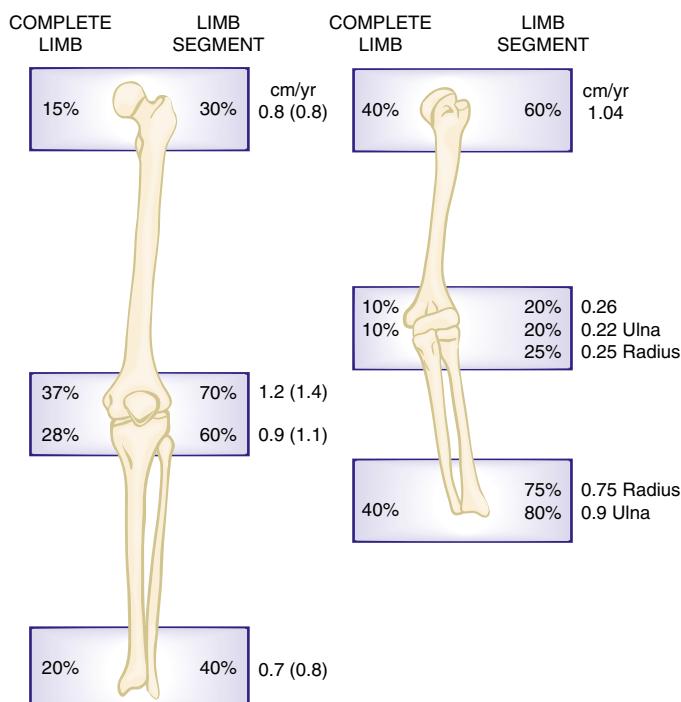


Fig. 713.4 The contribution (%) of each physis to the overall length of the extremities. (From Morrissey R, Weinstein S, eds. Lovell and Winter's Pediatric Orthopedics, 5th ed. Philadelphia: Lippincott Williams & Wilkins, 2001.)

Table 714.1

Characterization of Pain and Presenting Symptom

- Location:** Whether pain is localized to a particular segment or involves a larger area.
- Intensity:** Usually on a pain scale of 1-10 to indicate severity.
- Quality:** Tumor pain is often unrelenting, progressive, and present during the night. Pain at night particularly suggests osteoid osteoma. Pain in inflammation and infection is usually continuous.
- Onset:** Was it acute and related to specific trauma or was it insidious? Acute pain and history of trauma are more commonly associated with fractures.
- Duration:** Whether transient, only lasting for minutes, or lasting for hours or days. Pain lasting for longer than 3-4 weeks suggests a serious underlying problem.
- Progress:** Whether static, increasing, or decreasing.
- Radiation:** Pain radiating to upper or lower extremities or complaints of numbness, tingling, or weakness require appropriate workup.
- Aggravating factors:** Relationship to any activities, movements, or particular positions.
- Alleviating factors:** Is the pain relieved by rest, heat/ice, and/or medication? Conditions such as spondylylosis, Scheuermann disease, inflammatory spondyloarthropathy, muscle pulls, or overuse are improved by bed rest.
- Gait and posture:** Disturbances associated with pain.

vitamins, use of drugs or opiates, alcohol consumption, diabetes, immunization status (including receipt of rubella vaccine), and sexually transmitted infections. The child's prenatal and perinatal history should include information about the length of pregnancy, length of labor, type of labor (induced or spontaneous, Cesarean or vaginal delivery), presentation of fetus (cephalic or breech), birth trauma, evidence of any fetal distress at delivery, requirement for supplemental oxygen after the delivery, birth length and weight, Apgar score, muscle tone at birth, feeding history, and period of hospitalization. In older infants and young children, evaluation of developmental milestones for posture, locomotion, dexterity, social activities, and speech are important. Specific orthopedic questions should focus on joint, muscular, appendicular, or axial skeleton complaints. Information regarding pain or other symptoms in any of these areas should be elicited (Table 714.1). The family history can give clues to heritable disorders. It also can forecast expectations of the child's future development and allow appropriate interventions as necessary.

PHYSICAL EXAMINATION

The orthopedic physical examination includes a thorough examination of the musculoskeletal system along with a comprehensive neurologic examination. The examination may vary depending on the age of the child. The musculoskeletal examination includes inspection, palpation, and evaluation of motion, strength, stability, and gait. A basic neurologic examination includes sensory examination, motor function, and reflexes. The orthopedic physical examination requires basic knowledge of anatomy of joint range of motion, alignment, and stability. Many common musculoskeletal disorders can be diagnosed by the history and physical examination alone. One screening tool that has been useful in children is the pediatric gait, arms, legs, spine (pGALS) test, the components of which are shown in Figure 714.1.

Inspection

Initial examination of the child begins with inspection. The patient should be *comfortable with adequate exposure and well-lit surroundings* (lest some important physical findings be missed). Infants or young children may be examined on their parent's lap so that they feel more secure and are more likely to be cooperative. The clinician should use the guidelines listed in Table 714.2 during inspection.

Palpation

Palpation of the involved region should include assessment of local temperature and tenderness; assessment for a swelling or mass, lymphadenopathy, spasticity or contracture, and bone or joint deformity; and evaluation of anatomic axis of limb and of limb lengths.

Chapter 714

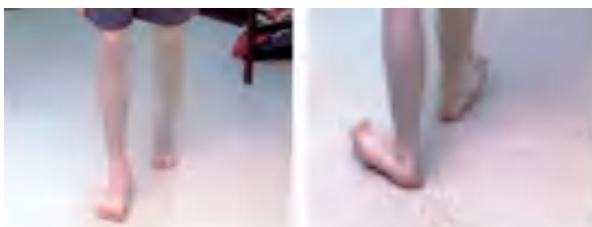
Orthopedic Evaluation of the Child

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A detailed history and thorough physical examination are critical to the evaluation of a child with an orthopedic problem. The child's family and acquaintances are important sources of information, especially in younger children and infants. Appropriate radiographic imaging and, occasionally, laboratory testing may be necessary to support the clinical diagnosis.

HISTORY

A comprehensive history should include details about the prenatal, perinatal, and postnatal periods. Prenatal history should include information about maternal health, including smoking history, use of prenatal

Gait

A "Walk on your tip-toes."
*Observe the child walking

B "Walk on your heels." *Observe the child walking

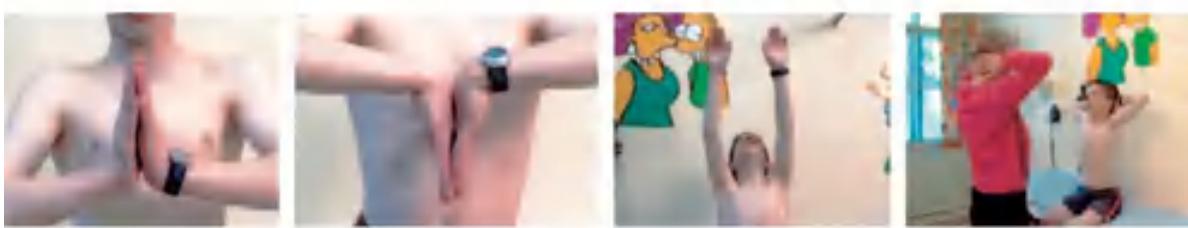
Arms

C "Put your hands out in front of you."

D "Turn your hands over and make a fist. Pinch your index finger and thumb together."

E "Touch the tips of your fingers with your thumb."

F Squeeze metacarpophalangeal joints



G "Put your hands together."*

H "Put your hands back to back."*

I "Reach up and touch the sky.* Look at the ceiling."

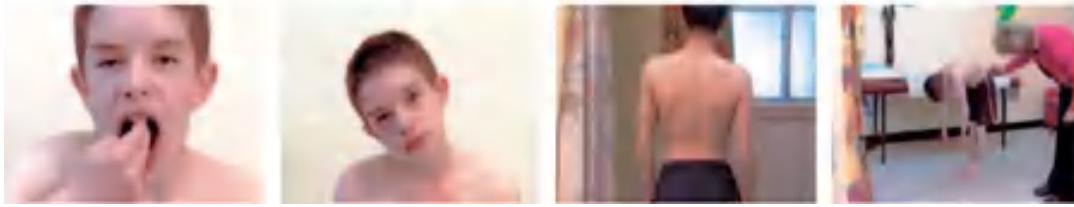
J "Put your hands behind your neck."

Legs

K Feel for effusion at the knee

L "Bend and then straighten your knee." (active movement of knees and examiner feels for crepitus)

M Passive flexion (90 degrees) with internal rotation of hip

Spine

N "Open your mouth and put 3 of your (child's own) fingers in your mouth."*

O Lateral flexion of cervical spine: "Try and touch your shoulder with your ear."

P Observe spine from behind

Q "Can you bend and touch your toes?" Observe curve of spine from side and behind

Fig. 714.1 The components of pediatric gait, arms, legs, spine (pGALS) screen, with illustration of movement. Screening questions: (1) Do you have any pain or stiffness in your joints, muscles, or back? (2) Do you have any difficulty getting yourself dressed without any help? (3) Do you have any difficulty going up and down stairs? *Additions and amendments to the original adult gait, arms, legs, spine screen. (From Foster HE, Kay LJ, Friswell M, et al. Musculoskeletal screening examination [pGALS] for school-age children based on the adult GALS screen. *Arthritis Rheum*. 2006;55:709-716.)

Table 714.2

Guidelines During Inspection of a Child with Musculoskeletal Problem

- It is important to inspect how the patient moves about in the room before and during the examination, as well as during various maneuvers. Balance, posture, and gait pattern should also be evaluated.
- General examination findings should include inspection for skin rashes, café-au-lait spots, hairy patches, dimples, cysts, tuft of hair, or evidence of spinal midline defects that can indicate serious underlying problems that need review.
- General body habitus*, including signs of cachexia, pallor, and nutritional deficiencies, should be noted.
- In the setting of trauma*, inspection of the injured limb should note deformity, swelling, erythema, and ecchymosis about a joint and/or long bone of the appendicular skeleton.
- Inspect the appendicular skeleton for evidence of deformity. Note if the deformity appears centered at a joint, bone, or within soft tissue. Attempt correction of the deformity to assess if it is correctible/flexible or fixed.
- Note any obvious spinal asymmetry, axial deformities, trunk decompensation, and evidence of muscle spasm or contractures. The *forward bending test* is valuable in assessing asymmetry and movement of the spine.
- Any discrepancies in limb lengths, as well as muscle atrophy, should be recorded.

Contractures are a loss of mobility of a joint from congenital or acquired causes and are caused by periarticular soft tissue fibrosis or involvement of muscles crossing the joint. Congenital contractures are common in **arthrogryposis** (see Chapter 723). Spasticity is an abnormal increase in tone associated with hyperreflexia and is common in cerebral palsy.

Deformity of the bone or joint is an abnormal fixed shape or position from congenital or acquired causes. It is important to assess the type of deformity, its location, and degree of deformity on clinical examination. It is also important to assess whether the deformity is fixed or can be passively or actively corrected, and whether there is any associated muscle spasm, local tenderness, or pain on motion. Classification of the deformity depends on the plane of deformity: **varus** (apex away from midline) or **valgus** (apex toward midline), or **flexion and extension** (in the sagittal plane). In the axial skeleton, especially the spine, deformity can be defined as scoliosis, kyphosis, hyperlordosis, and kyphoscoliosis (see Chapter 720).

Range of Motion

Active and passive joint motion should be assessed, recorded, and compared with the opposite side. Baseline flexibility or hypermobility beyond the range of normal motion should be noted. The **Beighton score** for hyperflexibility has been validated in children and serves to establish underlying laxity in the pediatric population (Table 714.3). Objective evaluation should be done with a goniometer and recorded.

Vocabulary for direction of joint motion is as follows:

Abduction: Away from the midline

Adduction: Toward the midline

Flexion: Movement of bending from the starting position

Extension: Movement from bending to the starting position

Hyperextension: Movement in extension beyond the starting position

Supination: Rotating the forearm to face the palm upward

Pronation: Rotating the forearm to face the palm downward

Inversion: Turning the hindfoot inward

Eversion: Turning the hindfoot outward

Plantar flexion: Pointing the toes away from the body (toward the floor)

Dorsiflexion: Pointing the toes toward the body (toward the ceiling)

Internal rotation: Turning inward toward the axis of the body

External rotation: Turning outward away from the axis of the body

Table 714.3

Beighton Grading for Hypermobility

DESCRIPTION	BILATERAL TESTING	SCORE (MAX. POINTS)
Passive dorsiflexion of the fifth metacarpophalangeal joint to >90 degrees	Yes	2
Passive hyperextension of the elbow >10 degrees	Yes	2
Passive hyperextension of the knee >10 degrees	Yes	2
Passive apposition of the thumb to the flexor side of the forearm, while shoulder is flexed 90 degrees, elbow is extended, and hand is pronated	Yes	2
Forward flexion of the trunk, with the knees straight, so that the palms of the hands rest easily on the floor	No	1
Total		9

From Smits-Engelsman B, Klerks M, Kirby A. Beighton Score: a valid measure for generalized hypermobility in children. *J Pediatr.* 2011;158:119–123. Table 1.

Table 714.4

Normal Upper Extremity Motion in Children in Degrees

MOTION	VALUE (IN DEGREES)
Shoulder elevation	180
Shoulder internal rotation	50–60
Shoulder external rotation	40–45
Shoulder extension	45–55
Shoulder internal rotation at 90 degrees of abduction	70
Shoulder external rotation at 90 degrees of abduction	100
Elbow flexion	145–150
Elbow extension	4–7

Adapted from Payares-Lizano M, Pino C. Pediatric orthopedic examination. *Pediatr Clin North Am.* 2020;67(1):1–21. Table 5; with additional data from McKay MJ, Baldwin JN, Ferreira P, et al. Normative reference values for strength and flexibility of 1,000 children and adults. *Neurology.* 2017;88(1):36–43.

Normal ranges of motion for the appendicular skeleton are noted in Table 714.4 (upper extremity), Table 714.5 (hip), and Table 714.6 (lower extremity).

NEUROLOGIC EVALUATION

A careful neurologic evaluation is part of every pediatric musculoskeletal examination (see Chapter 630). The assessment should include evaluation of developmental milestones, muscle strength (Table 714.7), sensory assessment, muscle tone, and deep tendon reflexes. The neurologic evaluation should also assess the spine and identify any deformity, such as scoliosis and kyphosis, or abnormal spinal mobility. The hips and feet should also be examined specifically, along with torsional

Table 714.5 Normal Hip Range of Motion in Children in Degrees

MOTION	AGE 2-5 (MALE/FEMALE)	AGE 6-10 (MALE/FEMALE)	AGE 11-17 (MALE/FEMALE)
Abduction	51/53	43/51	34/44
Adduction	17/18	15/18	14/17
Flexion	118/121	118/122	113/120
Extension	21/21	19/21	15/22
Internal rotation in flexion	45/47	40/41	35/35
External rotation in flexion	51/49	44/48	40/46
Internal rotation in extension	47/51	42/47	36/42
External rotation in extension	47/50	42/45	39/44

From Sankar WN, Laird CT, Baldwin KD. Hip range of motion in children: what is the norm? *J Pediatr Orthop.* 2012;32(4):399–405. **Table 1.**

Table 714.6 Normal Lower Extremity Motion in Children in Degrees

MOTION	AGE 3-9 (MALE/FEMALE)	AGE 10-19 (MALE/FEMALE)
Knee flexion	145/144	140/142
Knee extension	4/4	2/2
Ankle dorsiflexion	33/31	32/31
Ankle plantarflexion	63/63	58/63

Adapted from McKay MJ, Baldwin JN, Ferreira P, et al. Normative reference values for strength and flexibility of 1,000 children and adults. *Neurology.* 2017;88(1):36–43. Table e-4.

Table 714.8 Ashworth Scale of Spasticity

0	No increase in muscle tone
1	Slight increase in muscle tone, usually a catch or minimal resistance at end range of motion
2	Moderate tone throughout range of motion
3	Considerable increase in tone; passive range of motion difficult
4	Rigid in flexion or extension

Table 714.9 Clinical Scale of Extremity Motor Control

GRADE	DEFINITION
1	Hypotonic, no volitional motion
2	Hypertonic, no volitional motion
3	Mass flexion or extension in response to a stimulus
4	Patient can initiate movement but results in mass flexion or extension
5	Slow volitional movement; stress or rapid movement results in mass action
6	Volitional control of specific joints/muscles

Table 714.7 Medical Research Council (MRC) Scale for Muscle Strength

MUSCLE GRADE	DESCRIPTION
Grade 5	Normal
Grade 4	Movement against gravity and resistance
Grade 3	Movement against gravity over (almost) full range
Grade 2	Movement of the limb with gravity eliminated
Grade 1	Visible contraction without movement of the limb
Grade 0	No visible contraction

Data from Medical Research Council.

abnormalities of the lower extremity, which are vastly more common in the neurologically involved population. Specific peripheral nerve examinations may be necessary.

When the nervous system matures, the developing cerebral cortex normally inhibits rudimentary reflexes that are often present at birth (see [Chapter 630](#)). Therefore, persistence of these reflexes can indicate neurologic abnormality. The most commonly performed deep tendon reflex tests include biceps, triceps, quadriceps, and gastrocnemius and soleus tendons. Upper motor neuron signs should also be noted. The **Ashworth scale** is often used to grade spasticity ([Table 714.8](#)). Upper-extremity motor control is often graded, and these grades are useful both diagnostically and prognostically. Passive range of motion should be assessed to determine extremity motor control ([Table 714.9](#)). Localized or diffuse weakness must be

determined and documented. A thorough assessment and grading of muscle strength is mandatory in all cases of neuromuscular disorders (see [Table 714.7](#)).

Gait Assessment

Children typically begin walking between 8 and 16 months of age. Early ambulation is characterized by short stride length, a fast cadence, and slow velocity with a wide-based stance. The gait cycle is a single sequence of functions that starts with heel strike, foot flat, heel off, toe off, and swing. These events describe one gait cycle and include two phases: stance and swing. The stance phase is the period during which the foot is in contact with the ground. The swing phase is the portion of the gait cycle during which a limb is being advanced forward without ground contact. Normal gait is a symmetric and smooth process. Deviation from the norm indicates potential abnormality and should trigger investigation.

Neurologic maturation is necessary for the development of gait and the normal progression of developmental milestones. A child's

Table 714.10 Causes of Gait Disturbances**MECHANICAL**

Acute injuries (accidental or nonaccidental)
Overuse conditions (mainly sports-related)
Dysplastic lesions
Limb length discrepancy

OSSEOUS

Legg-Calvé-Perthes disease
Osteochondritis dissecans of knee and talus
Slipped capital femoral epiphysis
Osteomyelitis
Spondylodiscitis
Osteoid osteoma or other primary bone tumor

ARTICULAR

Developmental hip dysplasia
Septic arthritis
Transient synovitis
Rheumatic disease (juvenile idiopathic arthritis, systemic lupus erythematosus)
Hemophilia-related hemorrhage
Ankylosis of a joint

NEUROLOGIC

Guillain-Barré syndrome and other peripheral neuropathies
Intoxication
Cerebellar ataxia
Brain tumor
Lesion occupying spinal cord space
Posterior column spinal cord disorders
Myopathy
Hemiplegia
Complex regional pain syndrome
Cerebral palsy

HEMATOLOGIC/ONCOLOGIC

Sickle cell pain crisis
Leukemia, lymphoma
Metastatic tumor
Langerhans cell histiocytosis

OTHER

Soft tissue infection
Myositis
Fasciitis
Bursitis
Kawasaki disease
Conversion disorder
Gaucher disease
Phlebitis
Scurvy
Rickets
Peritonitis

From Kliegman RM, Lye PS, Bordini BJ, et al., eds. *Nelson Pediatric Symptom-Based Diagnosis*. Philadelphia: Elsevier; 2018: Table 34.1, p. 615.

gait changes with neurologic maturation. Toddlers normally walk with greater hip and knee flexion, flexed arms, and a wider base of gait than older children. As the neurologic system continues to develop in the cephalocaudal direction, the efficiency and smoothness of gait increase. The gait characteristics of a 7-year-old child are similar to those of an adult. When the neurologic system is abnormal (e.g., cerebral palsy), gait can be disturbed, exhibiting pathologic reflexes and abnormal movements.

Deviations from normal gait occur in a variety of orthopedic conditions. Disorders that result in muscle weakness (e.g., spina bifida, muscular dystrophy), spasticity (e.g., cerebral palsy), or contractures (e.g., arthrogryposis) lead to abnormalities in gait. Other causes of gait disturbances include limp, pain, torsional variations (in-toeing and out-toeing), toe walking, joint abnormalities, and leg-length discrepancy (Tables 714.10 and 714.11).

Table 714.11

Differential Diagnosis of Limping in Children by Age

AGE GROUP**DIAGNOSTIC CONSIDERATIONS**

Early walker:
1-3yr

PAINFUL LIMP
Septic arthritis and osteomyelitis
Transient synovitis
Fracture
Occult trauma (toddler's fracture)
Intervertebral diskitis
Malignancy
Abuse (nonaccidental trauma)
Rheumatologic disorders (e.g., juvenile idiopathic arthritis)

PAINLESS LIMP

Developmental dysplasia of the hip
Neuromuscular disorder
Polio
Cerebral palsy
Lower extremity length inequality

Child: 3-10yr

PAINFUL LIMP
Septic arthritis, osteomyelitis, myositis
Transient synovitis
Trauma, fracture
Rheumatologic disorders
Spondylodiscitis
Malignancy

PAINLESS LIMP

Developmental dysplasia of the hip
Legg-Calvé-Perthes disease
Lower extremity length inequality
Neuromuscular disorder (e.g., muscular dystrophy)
Polio
Cerebral palsy

Adolescent:
11 yr to maturity

PAINFUL LIMP
Septic arthritis, osteomyelitis, myositis
Trauma (including overuse injuries and fractures)
Rheumatologic disorder
Slipped capital femoral epiphysis (acute, unstable)
Malignancy
Osteochondritis dissecans

PAINLESS LIMP

Slipped capital femoral epiphysis (chronic, stable)
Developmental dysplasia of the hip (acetabular dysplasia)
Lower extremity length inequality
Neuromuscular disorder

Modified from Marcante K, Kliegman R, eds. *Nelson Essentials of Pediatrics*, 7th ed. Philadelphia: Saunders, 2015.

LIMPING

A thorough history and clinical examination are the first steps toward early identification of the underlying problem causing a limp. Limping can be considered either **painful (antalgic)** or **painless**, with the differential diagnosis ranging from benign to serious causes (e.g., septic hip, tumor). In a painful gait, the stance phase is shortened as the child decreases the time spent on the painful extremity. In a painless gait, which indicates underlying proximal muscle weakness or hip instability, the stance phase is equal between the involved and unininvolved sides, but the child leans or shifts the center of gravity over the involved extremity for balance. A bilateral disorder produces a waddling gait. **Trendelenburg gait** (i.e., trunk lists to the affected side with each step) is produced by weak abnormal hip abductors. When the patient stands on one foot, a **Trendelenburg sign** (i.e., sagging rather than rising of

the unsupported buttock) can often be elicited when abductors are weak.

Disorders most commonly responsible for an abnormal gait generally vary based on the age of the patient. The differential diagnosis of limping varies based on age group (see Table 714.11) or mechanism. Neurologic disorders, especially spinal cord, muscle, or peripheral nerve disorders, can also produce limping and difficulty walking. Antalgic gait is predominantly a result of trauma, infection, or pathologic fracture. Trendelenburg gait is generally caused by congenital, developmental, or muscular disorders. In some cases, limping also may be caused by nonskeletal causes, such as testicular torsion, inguinal hernia, and appendicitis.

BACK PAIN

Children frequently have a specific skeletal pathology as the cause of back pain. The most common causes of back pain in children are trauma, spondylolysis, spondylolisthesis, and infection (see Chapter 720.5). Tumor and tumor-like lesions that cause back pain in children are likely to be missed unless a thorough clinical assessment and adequate workup are performed when required. Nonorthopedic causes of back pain include urinary tract infections, nephrolithiasis, and pneumonia.

RADIOGRAPHIC ASSESSMENT

Plain radiographs are the first step in evaluation of most musculoskeletal disorders. Advanced imaging includes MRI, nuclear bone scans, ultrasonography, CT, and positron emission tomography. Rapid short tau inversion recovery (STIR) MRI is a valuable screening test if a specific location is not well defined.

Plain Radiographs

Routine radiographs consist of anteroposterior and lateral views of the involved area with inclusion of one joint above and below the site of symptoms. Comparison views of the opposite side, if uninvolvled, may be helpful in difficult situations but are not always necessary. Specialized views for each joint, such as oblique views, may offer more specific and tailored imaging for an individual fracture or other condition. It is important for the clinician to be aware of normal radiographic variants of the immature skeleton, including when to expect to see development and ultimately closure of growth centers about the joints. Several synchondroses may be mistaken for fractures. A patient with "normal" plain radiographic appearance but having persistent pain or symptoms might need to be evaluated further with additional imaging studies.

Ultrasonography

Ultrasonography is useful to evaluate suspected fluid-filled lesions such as popliteal cysts and hip joint effusions. Major indications for ultrasonography are fetal studies of the extremities and spine (including detection of congenital anomalies like spondylocostal dysostosis or osteogenesis imperfecta), developmental dysplasia of the hip in children 6 weeks to 6 months of age, joint effusions, occult neonatal spinal dysraphism, foreign bodies in soft tissues, and popliteal cysts of the knee.

Magnetic Resonance Imaging

MRI is the imaging modality of choice for defining the exact anatomic extent of most musculoskeletal lesions (particularly if the structure is soft tissue). MRI avoids ionizing radiation and does not cause any known harmful effects. It produces excellent anatomic images of the musculoskeletal system, including the soft tissue, bone marrow cavity, spinal cord, and brain. It is especially useful

for defining the extent of soft tissue lesions, infections, and injuries. Tissue planes are well delineated, allowing more accurate assessment of tumor invasion into adjacent structures. Cartilage structures can be visualized and differentiated (e.g., articular cartilage of the knee can be distinguished from the fibrocartilage of the meniscus). MRI is also helpful in visualizing unossified joints in the pediatric population, including the shoulders, elbows, and hips of young infants.

Magnetic Resonance Angiography

Magnetic resonance angiography (MRA) has largely replaced routine angiography in the preoperative assessment of vascular lesions and bone tumors. MRA provides good visualization of peripheral vascular branches and tumor neovascularity in patients with primary bone tumors.

Computed Tomography

CT has enhanced the evaluation of multiple musculoskeletal disorders. Coronal, sagittal, and axial imaging is possible with CT, including three-dimensional reconstructions that can be beneficial in evaluating complex lesions of the axial and appendicular skeleton. It allows for visualization of the detailed bone anatomy and the relationship of bones to contiguous structures. CT is useful to readily evaluate tarsal coalition, accessory navicular bone, infection, growth plate arrest, osteoid osteoma, pseudoarthrosis, femoroacetabular impingement, complex fracture patterns (periarticular and intra-articular), bone and soft tissue tumors, spondylolysis, and spondylolisthesis. CT is superior to MRI for assessing bone involvement and cortical destruction (even subtle changes), including calcification or ossification and fracture (particularly if displacement of an articular fracture is suspected).

Nuclear Medicine Imaging

A bone scan displays physiologic information rather than pure anatomy and relies on the emission of energy from the nucleotide injected into the patient. Indications include early septic arthritis, osteomyelitis, avascular necrosis, tumors (osteoid osteoma), metastatic lesions, occult and stress fractures, and cases of nonaccidental trauma.

Total-body radionuclide scan (technetium-99) is useful to identify bony lesions, inflammatory tumors, and stress fractures. Tumor vascularity can also be inferred from the flow phase and the blood pool images. Gallium or indium scans have high sensitivity for local infections. Thallium-201 chloride scintiscans have >90% sensitivity and 80–90% accuracy in detecting malignant bone or soft tissue tumors. *MRI has supplanted nuclear medicine imaging in many circumstances.*

LABORATORY STUDIES

Laboratory tests are occasionally necessary in the evaluation of a child with musculoskeletal disorder. These may include a complete blood cell count; erythrocyte sedimentation rate; C-reactive protein assay; Lyme titers; and blood, wound, joint, periosteum, or bone cultures for infectious conditions such as septic arthritis or osteomyelitis. Rheumatoid factor, antinuclear antibodies, and human leukocyte antigen B27 may be necessary for children with suspected rheumatologic disorders. Creatine kinase, aldolase, aspartate aminotransferase, and dystrophin testing are indicated in children with suspected disorders of striated muscle, such as Duchenne muscular dystrophy.

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Chapter 715

The Foot and Toes

Christine M. Goodbody, Jennifer J. Winell,
and Richard S. Davidson

Abnormalities affecting the osseous and articular structures of the foot may be congenital, developmental, neuromuscular, inflammatory, or acquired. Problems with the foot and/or toes may be associated with a host of connective tissue diseases and syndromes, and overuse syndromes are commonly observed in young athletes. Symptoms may include pain and difficulty with shoe wear, and cosmetic concerns are common. The foot may be divided into the **forefoot** (toes and metatarsals), the **midfoot** (cuneiforms, navicular, cuboid), and the **hindfoot** (talus and calcaneus). Although the tibiotalar joint (ankle) provides plantarflexion and dorsiflexion, the subtalar joint (between the talus and calcaneus) is oriented obliquely, providing inversion and eversion. Inversion represents a combination of plantarflexion and varus, whereas eversion involves dorsiflexion and valgus. The subtalar joint is especially important for walking on uneven surfaces. Inversion of the transverse tarsal (Chopart) joint locks the midfoot to provide a stable base on which to perform toe-off during the gait cycle. Eversion of the transverse tarsal joint unlocks the **hindfoot** to provide accommodation during heel strike of the gait cycle. The talonavicular and calcaneocuboid joints connect the midfoot with the hindfoot.

715.1 Metatarsus Adductus

Christine M. Goodbody, Jennifer J. Winell, and
Richard S. Davidson

Metatarsus adductus involves adduction of the forefoot relative to the hindfoot. When the forefoot is adducted, and sometimes in supination, the deformity is termed *metatarsus varus* (Fig. 715.1). The disorder is common in newborns, most frequently caused by intrauterine molding (deformation); the deformity is bilateral in 50% of cases. A careful hip and neck examination must always be performed to look for other abnormalities associated with intrauterine positioning.

CLINICAL MANIFESTATIONS

The forefoot is adducted (occasionally supinated), whereas the midfoot and hindfoot are normal. The lateral border of the foot is convex, and the base of the fifth metatarsal appears prominent. Range of motion at the ankle and subtalar joints is normal. Both the magnitude and the degree of flexibility should be documented. When the normal foot is viewed from the plantar surface, a line through the midpoint of (and parallel to) the heel should extend through the second toe. In metatarsus adductus, the line extends laterally to the second toe. Flexibility is assessed by stabilizing the hindfoot and midfoot in a neutral position with one hand and applying pressure over the first metatarsal head with the other. Correction with little pressure is indicative of a more flexible deformity. In the walking child with an uncorrected metatarsus adductus deformity, an in-toe gait and abnormal shoe wear may occur. A subset of patients will also have a dynamic adduction deformity of the great toe (hallux varus), which is often most noticeable during ambulation. This usually improves spontaneously and does not require treatment.

RADIOGRAPHIC EVALUATION

Radiographs are not performed routinely in infants with metatarsus adductus. Older children with residual deformity should have anteroposterior (AP) and lateral weight-bearing or simulated weight-bearing radiographs. The AP radiographs demonstrate adduction of the metatarsals at the tarsometatarsal articulation and an increased intermetatarsal angle between the first and second metatarsals.

TREATMENT

The treatment of metatarsus adductus is based on the rigidity of the deformity, but most children respond to nonoperative treatment. Deformities that are flexible and overcorrect into abduction with passive manipulation may be observed. Those feet that correct just to a neutral position may benefit from stretching exercises, which can be demonstrated to the parents in the office. In a walking child, the parents can try reversing the shoes as well. If this is not effective, reverse-last shoes can be prescribed to maintain the abducted position of foot. These are worn full-time (22 hours/day), and the condition is reevaluated in 4–6 months. The position of the heel bisector can be followed over the course of observation or treatment to monitor for improvement. If improvement occurs, treatment can be continued for an additional year or more. If there is no improvement, serial plaster casts should be considered. When stretching a foot with metatarsus adductus, care should be taken to maintain the hindfoot in neutral to slight varus alignment to avoid creating hindfoot valgus. Feet that cannot be corrected to a neutral position may benefit from initial serial casting; the best results are obtained when treatment is started before 8 months of age. In addition to stretching the soft tissues, the goal is to alter physeal growth and stimulate remodeling, resulting in permanent correction. Once flexibility and alignment are restored, orthoses, corrective shoes, or wearing shoes on opposite feet is generally recommended for 6–12 months. A dynamic hallux varus usually improves spontaneously, and no active treatment is required.

Surgical treatment may be considered in the small subset of patients with symptomatic residual deformities who have not responded to treatment. Surgery is generally delayed until children are 4–6 years of age. Cosmesis is often a concern, and pain and/or the inability to wear certain types of shoes may occasionally lead patients to consider surgery.

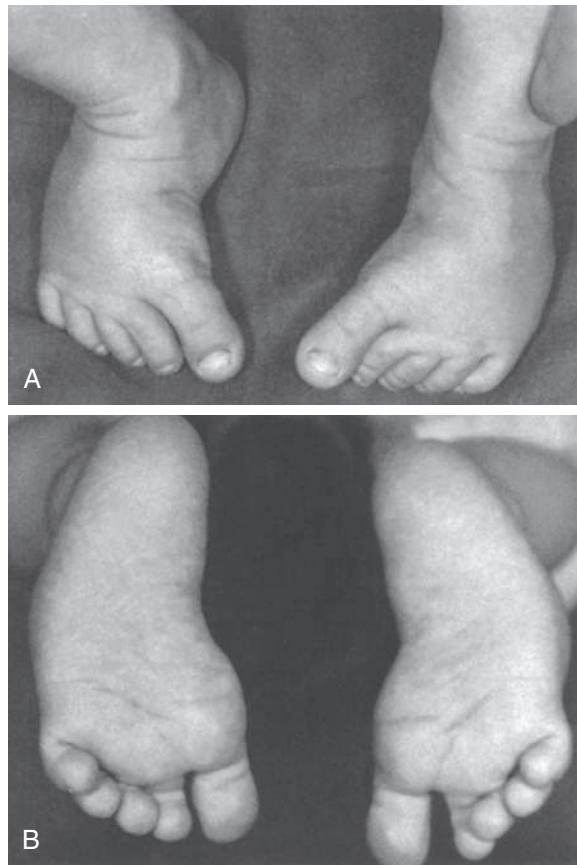


Fig. 715.1 Bilateral mild metatarsus adductus. A, Dorsal view showing medial deviation of all the metatarsals. B, Plantar view showing the “bean-shaped” foot. This type of foot is easily corrected with serial casting. (From Ricco Al. Disorders of the foot. In: Herring JA, ed. Tachdjian’s Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig. 19-19.)

Options for surgical treatment include either soft tissue releases or osteotomies depending on age, anatomy, deformity flexibility, and other patient-specific factors. An osteotomy (midfoot or multiple metatarsals) is most likely to result in permanent restoration of alignment.

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715.2 Calcaneovalgus Feet

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

A common finding in the newborn, the calcaneovalgus foot occurs secondary to in utero positioning (deformation). Excessive dorsiflexion and eversion are observed in the hindfoot, and the forefoot may be abducted. There may be an associated external tibial torsion (see Chapter 716).

CLINICAL MANIFESTATIONS

The infant typically presents with the foot dorsiflexed and everted, and occasionally the dorsum of the foot or toes will be in contact with the anterolateral surface of the lower leg (Fig. 715.2). Dimpling may be indicative of reduced subcutaneous fat at the dorsolateral ankle. Plantarflexion and inversion are often restricted. A careful hip examination should be performed, and if there is any concern, hip ultrasonography should be considered. When comparing risk for developmental dysplasia of the hip (DDH) with other congenital foot deformities, congenital calcaneovalgus has the highest association, with 6.1–19.4% of patients having coexisting DDH. The calcaneovalgus foot may be confused with a congenital vertical talus and may rarely be associated with a posteromedial bow of the tibia. A calcaneovalgus deformity also may be seen in older patients, typically those with a neuromuscular imbalance involving weakness or paralysis of the gastrosoleus muscle (e.g., polio, myelomeningocele).

RADIOGRAPHIC EVALUATION

Radiographs are usually not required but should be ordered if the deformity fails to correct spontaneously or with early treatment. AP and lateral radiographs along with a lateral radiograph of the foot in maximal plantarflexion may help distinguish calcaneovalgus from a congenital vertical talus or congenital oblique talus. Evaluation of the position of the talus in relation to the navicular in both the lateral and maximally plantarflexed lateral view can help to diagnose congenital vertical or oblique talus. If a posteromedial bow of the tibia is suspected, AP and lateral radiographs of the tibia and fibula are necessary. In posteromedial bowing of the tibia, the deformity is located in the tibia with the apex of deformity positioned posterior and medial. All three conditions may be confused clinically with calcaneovalgus feet.

TREATMENT

Mild cases of calcaneovalgus foot, in which full passive range of motion is present at birth, require no active treatment. These usually resolve within the first few weeks of life. A gentle stretching program focusing on plantarflexion and inversion is recommended for cases with some restriction in motion. For cases with a greater restriction in mobility, serial casts may be considered to restore motion and alignment, although casting is rarely required in the treatment of calcaneovalgus feet. Unresponsive cases should be evaluated for associated neuromuscular or other etiologies.

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715.3 Talipes Equinovarus (Clubfoot)

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

Clubfoot or congenital talipes equinovarus (CTEV) is the term used to describe a deformity involving malalignment of the calcaneotalar-navicular complex. Components of this deformity may be

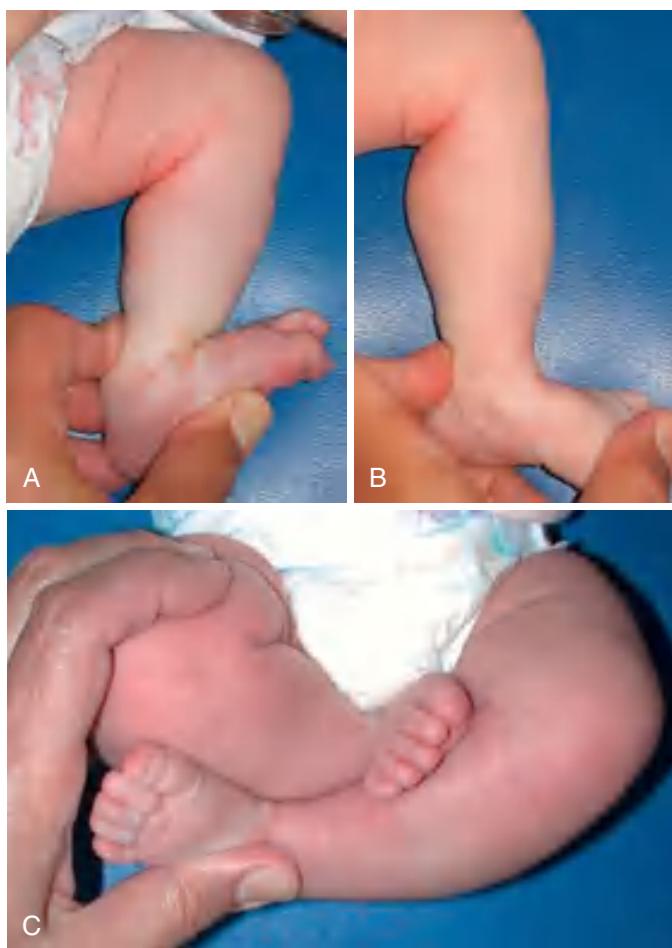


Fig. 715.2 Clinical picture of calcaneovalgus foot (A) that is passively correctable (B) and is due to intrauterine positioning (C).

best understood using the mnemonic **CAVE** (cavus:midfoot, adductus:forefoot, varus:heel, equinus:hindfoot). Although this is predominantly a hindfoot deformity, it involves plantarflexion (cavus) of the first ray (the first metatarsal and first cuneiform) and adduction of the forefoot/midfoot on the hindfoot. The hindfoot is in varus and equinus. The clubfoot deformity may be positional, congenital, associated with a variety of underlying diagnoses (neuromuscular or syndromic), or a focal dysplasia of musculoskeletal tissue distal to the knee.

The **positional (or postural) clubfoot** is a normal foot that has been held in a deformed position in utero and is found to be flexible on examination in the newborn nursery. The nonpositional **congenital clubfoot** can either be idiopathic or syndromic. There is a spectrum of severity, but clubfoot associated with neuromuscular diagnoses or syndromes is typically rigid and more difficult to treat. Clubfoot is also extremely common in patients with myelodysplasia, arthrogryposis, and chromosomal syndromes such as trisomy 18 and chromosome 22q11 deletion syndrome (see Chapter 99).

Congenital clubfoot is seen in approximately 1-2 in 1,000 births and most likely results from a complex multifactorial polygenic inheritance. The risk is ~25% when both a parent and one sibling have clubfeet. It occurs more commonly in males (2:1) and is bilateral in 50% of cases. The pathoanatomy involves both abnormal tarsal morphology (plantar and medial deviation of the head and neck of the talus) and abnormal relationships between the tarsal bones in all three planes, as well as associated contracture of the soft tissues on the plantar and medial aspects of the foot.

CLINICAL MANIFESTATIONS

A complete physical examination should be performed to rule out coexisting musculoskeletal and neuromuscular problems. The spine should be inspected for signs of occult dysraphism. Examination of the infant

clubfoot demonstrates forefoot cavus and adductus and hindfoot varus and equinus (Fig. 715.3). The degree of flexibility varies, and all patients will exhibit calf atrophy. Internal tibial torsion, foot length shortening, and leg-length discrepancy (shortening of the ipsilateral extremity) will be observed in a subset of cases. Although classically not associated with DDH (see Chapter 719.1), there is a higher association of CTEV and DDH than in the general population.

RADIOGRAPHIC EVALUATION

AP and lateral radiographs are not recommended for idiopathic clubfoot. For arthrogryotic or syndromic feet, x-rays may be helpful but must be performed with the foot held in the maximally corrected position. The lateral x-ray should be a trans-malleolar view. Multiple radiographic measurements can be made to describe malalignment between the tarsal bones. The navicular bone does not ossify until 3–6 years of age, so the focus of radiographic interpretation is the relationship between segments of the foot, forefoot to hindfoot. A common radiographic finding is “parallelism” between lines drawn through the axis of the talus and the calcaneus on the lateral radiograph, indicating hindfoot varus. X-ray may be particularly useful for older children with persistent or recurrent deformities that are difficult to assess.

TREATMENT

Nonoperative treatment is initiated in all infants and should be started as soon as possible following birth. Techniques have included taping and strapping, manipulation and serial casting, and functional treatment. Historically, a significant percentage of patients treated by manipulation and casting required a surgical release, which was usually performed between 3 and 12 months of age. Although many feet remain well aligned after surgical releases, a significant percentage of patients require additional surgery for recurrent or residual deformities, and stiffness remains a concern at long-term follow-up. While pain is uncommon in childhood and adolescence, symptoms may appear during adulthood. These concerns have led to considerable interest in less-invasive methods for treating the deformity.

The Ponseti method of clubfoot treatment, which is the standard of initial treatment, involves a specific technique for manipulation and serial casting, and may be best described as minimally invasive rather than nonoperative (Fig. 715.4). The order of correction follows the mnemonic CAVE. Weekly cast changes are performed; 5–10 casts are typically required. The most difficult deformity to correct is the hindfoot equinus, and ~90% of patients will require a percutaneous tenotomy of the heel cord

under local anesthesia as an outpatient. Following the tenotomy, a long leg cast with the knee flexed 90 degrees and the foot in maximal abduction (up to 70 degrees) with 0–10 degrees of dorsiflexion is worn for 3–4 weeks. The patient then begins a bracing program. An abduction brace (bars and shoes) is worn 22 hours a day for 3 months and then at night-time until the age of 3–5 years. A small subset of patients (up to 20%) with recurrent, dynamic supination deformity will require transfer of the tibialis anterior tendon to the lateral cuneiform. The results of the Ponseti method are excellent at up to 40 years of follow-up. Despite casting, children do not have much dysfunction or delay in achieving normal motor milestones. Compliance with the bracing program is essential as recurrence is common if the brace is not worn as recommended. Minimally invasive methods are most successful when treatment is begun at birth or during the first few months of life, and with good compliance with postmanipulation bracing.

Aggressive surgical realignment has a definite role in the management of clubfeet, especially in the minority of *congenital* clubfeet that have failed nonoperative or minimally invasive methods, and for the neuromuscular and rigid syndromic clubfeet. In such cases, minimally invasive methods such as the Ponseti technique may potentially be of value in decreasing the need for surgery or the magnitude of surgery required. Common surgical approaches include a release of the involved joints (realignment of the tarsal bones), a lengthening of the shortened posteromedial musculotendinous units, and usually pinning of the foot in the corrected position. The “a la carte” method allows the surgeon to apply the principles of deformity correction to be tailored to the unique characteristics of each deformity. For older children with untreated clubfeet or those in whom a recurrence or residual deformity is observed, bony procedures (osteotomies) may be required in addition to soft tissue surgery. Triple arthrodesis is reserved as salvage for painful, deformed feet in adolescents and adults.

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715.4 Congenital Vertical Talus

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

Congenital vertical talus is an uncommon foot deformity in which the midfoot is dorsally dislocated on the hindfoot and the ankle is in fixed equinus. A variant form, called oblique talus, refers to subluxation of

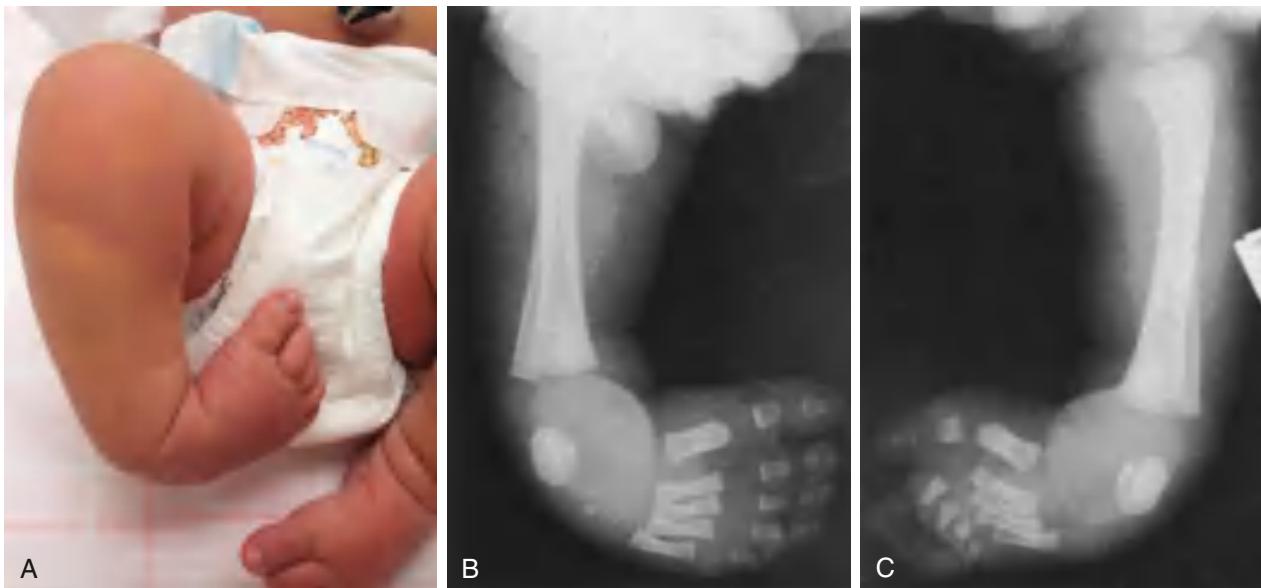


Fig. 715.3 Talipes equinovarus in a newborn. A, Clinical appearance of an untreated clubfoot. B and C, Initial radiographic appearance of bilateral untreated clubfeet. (From Ricco Al. Disorders of the foot. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig. 19-42.)



Fig. 715.4 Ponseti method of clubfoot treatment. Ponseti casts show serial correction of the patient (A-F). The last cast (E and F) was applied after percutaneous heel cord tenotomy. (From Ricco AI. Disorders of the foot. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig. 19.47, p. 717.)

the talonavicular joint and is usually neuromuscular in origin. There is nearly an even split between idiopathic cases and cases with an underlying neuromuscular condition or a syndrome. Neurologic causes include myelodysplasia, tethered cord, and sacral agenesis. Other associated conditions include arthrogryposis, Larsen syndrome, multiple pterygium syndrome, and chromosomal abnormalities (trisomy 13–15, 19; see Chapter 99). Depending on the age at diagnosis, the differential diagnosis may include a calcaneovalgus foot, oblique talus (talonavicular joint reduces passively), flexible flatfoot with a tight Achilles tendon, and tarsal coalition.

CLINICAL MANIFESTATIONS

Congenital vertical talus has also been described as a **rocker-bottom foot** (Fig. 715.5). The plantar surface of the foot is convex, and the talar head is prominent along the medial border of the midfoot. The forefoot is dorsiflexed (dorsally dislocated) and abducted relative to the hindfoot, and the hindfoot is in equinus and valgus. There is an associated contracture of the anterolateral (toe extensors) and the posterior (Achilles tendon, peroneals) soft tissues, which may overpower a weakened posterior tibialis and toe flexors. The deformity is typically rigid in vertical talus

and flexible in oblique talus. Physical examination is required to identify any coexisting neurologic and/or musculoskeletal abnormalities.

RADIOGRAPHIC EVALUATION

AP, lateral, and maximal plantarflexion, and dorsiflexion lateral radiographs should be obtained when the diagnosis is suspected. The maximum plantarflexion view helps determine whether the dorsal subluxation or dislocation of the midfoot on the hindfoot can be reduced passively, that is, if the navicular can be aligned with the talus. The dorsiflexion lateral view confirms the equinus contracture of the ankle. Although the navicular does not ossify until 3–6 years of age, in younger patients the relationship between the talus and the first metatarsal may be evaluated.

TREATMENT

The initial management consists of serial manipulation and casting, which is started shortly after birth. A *reverse Ponseti* method of casting is particularly useful in stretching out the dorsiflexion and valgus deformities. Open reduction and pin fixation can then stabilize the midfoot, allowing simultaneous heel cord tenotomy and dorsiflexion with casting to correct the ankle equinus.

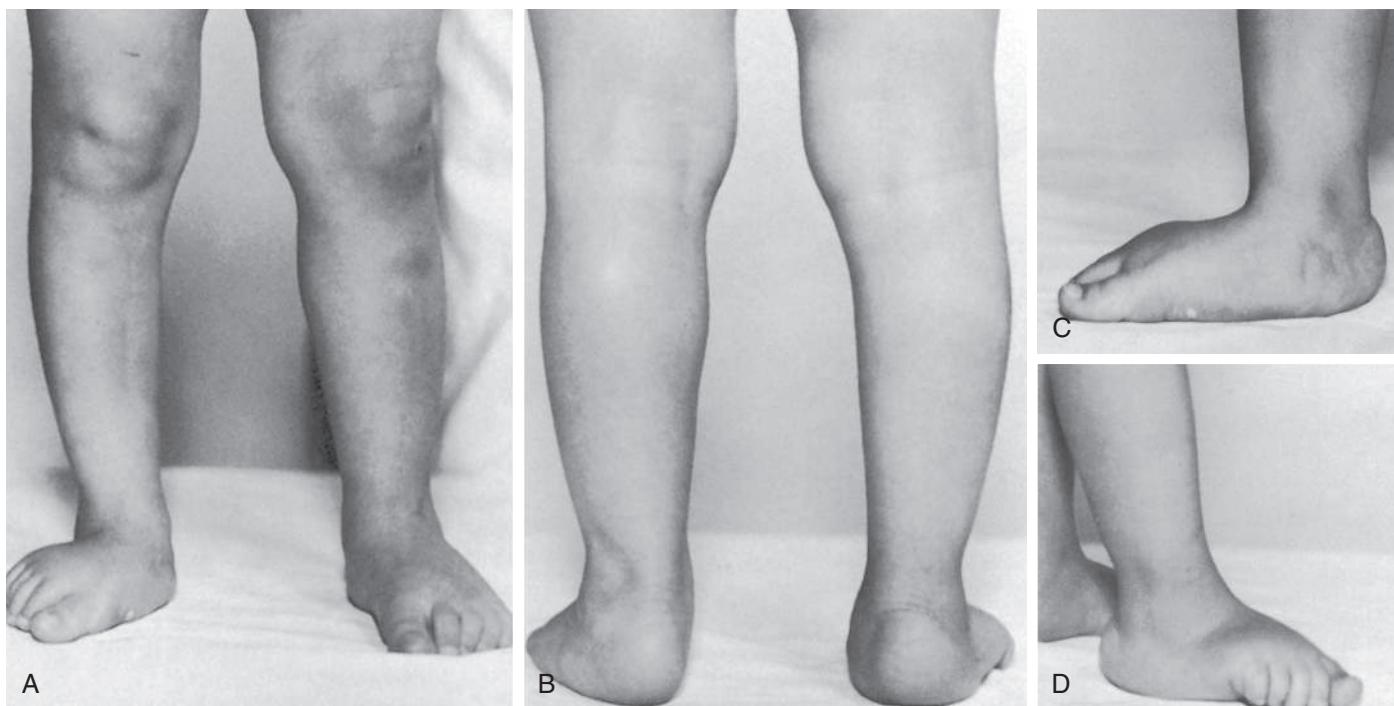


Fig. 715.5 Congenital vertical talus. A, Pronation of the forefoot. B, Valgus of the heel. C, Absence of an arch, the rocker bottom deformity. D, Elevation of the lateral toes and tight peroneal tendons. (From Ricco AI. Disorders of the foot. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig. 19-67.)

In recalcitrant cases, the competing deformities of the midfoot and the hindfoot make conservative treatment difficult. Initially an attempt is made to reduce the dorsal dislocation of the forefoot/midfoot on the hindfoot. Once this has been achieved, attention can be directed toward stretching the hindfoot contracture. These deformities are typically rigid, and surgical intervention is required in the majority of cases. In such cases, casting still helps to stretch out the contracted soft tissues to minimize the magnitude of surgical correction required. Surgery is generally performed between 3 and 12 months of age as a one-stage procedure. This involves release/lengthening of the contracted anterior soft tissues in concert with an open reduction and wire fixation of the talonavicular joint, followed by a posterior release with lengthening of the contracted musculotendinous units. Fixation with Kirschner wires is commonly performed to maintain alignment. Postoperatively, casting is employed for a variable period of time, and afterward patients often require the use of an orthosis for extended periods, depending on the underlying diagnosis. Salvage options for recurrent or residual deformities in older children include a subtalar or triple arthrodesis.

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715.5 Hypermobile Pes Planus (Flexible Flatfeet)

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

Flatfoot is a common diagnosis, and it has been estimated that up to 23% of the public may be affected, depending on the diagnostic criteria employed. Three types of flatfeet may be identified: a flexible flatfoot, a flexible flatfoot with a tendo-Achilles contracture, and a rigid flatfoot. Flatfoot describes a change in foot shape, and there are several abnormalities in alignment between the tarsal bones. There is eversion of the subtalar complex, valgus alignment of the hindfoot, and midfoot sag at the naviculocuneiform and/or the talonavicular joints. Additionally, the forefoot is abducted relative

to the hindfoot, and the head of the talus is uncovered and prominent along the plantar and medial border of the midfoot/hindfoot. Although hypermobile or flexible pes planus represents a common source of concern for parents, these children are rarely symptomatic. Flatfeet are common in neonates and toddlers and are associated with physiologic ligamentous laxity. Improvement or correction is seen as the longitudinal arch develops between 5 and 10 years of age in the vast majority of children. Flexible flatfeet persisting into adolescence and adulthood are usually associated with **familial ligamentous laxity (hypermobility syndromes)** and often can be identified in other family members.

Patients typically have a normal longitudinal arch when examined in a non-weight-bearing position or standing on the toes, but the arch flattens when weight-bearing. The hindfoot collapses into valgus, and the midfoot sag becomes evident. The forefoot is supinated in weight-bearing. Generalized hypermobility and ligamentous laxity are often observed. Range of motion should be assessed at both the subtalar and the ankle joints. If the heel cord is tight, the flexible flatfoot may become painful. When assessing range of motion at the ankle, the hindfoot should always be inverted while testing dorsiflexion to lock subtalar eversion and apparent dorsiflexion. If the foot is neutral or everted, spurious dorsiflexion may occur through the midfoot, masking a tendo-Achilles contracture. If subtalar motion is restricted, the flatfoot is considered "rigid," and other diagnoses, such as tarsal coalition and juvenile rheumatoid arthritis, must be considered. On occasion, there may be tenderness and/or callus formation under the talar head medially. The shoes should be assessed as well and may have evidence of excessive wear along the medial border.

RADIOGRAPHIC EVALUATION

Routine radiographs of asymptomatic flexible flatfeet are usually not indicated. If obtained for diagnostic reasons, weight-bearing radiographs (AP and lateral) are required to assess the deformity. The foot should be positioned in the child's normal stance as medial rotation and hindfoot inversion may falsely correct the flatfoot. On the AP radiograph, there is widening of the angle between the longitudinal axis of the talus and the calcaneus, indicating excessive heel valgus, as well as talonavicular uncoverage and forefoot abduction. The lateral

view shows decreased calcaneal pitch to the tibia and distortion of the normal straight-line relationship between the long axis of the talus and the first metatarsal (i.e., Meary angle) with sag, either of the talonavicular or naviculocuneiform joint, resulting in flattening of the normal medial longitudinal arch (Fig. 715.6).

TREATMENT

Although the natural history of the flexible flatfoot remains unknown, there is little evidence to suggest that this condition results in long-term problems or disability. As such, treatment is reserved for the small subset of patients who develop symptoms. Patients may complain of hindfoot pain, difficulty with shoe wear, or fatigue after long walking. These patients may benefit from a nonprescription orthosis, such as a medial arch support. However, tight heel cords, when present, must be corrected before using arch supports. Severe cases, often associated with an underlying connective tissue disorder such as Ehlers-Danlos syndrome (see Chapter 744) or Down syndrome (see Chapter 99), may benefit from a custom orthosis such as the UCBL (University of California Biomechanics Laboratory) orthosis to better control the hindfoot and prevent collapse of the arch. Although an orthosis may relieve symptoms, there is no evidence to suggest any permanent change in the shape of the foot or alignment of the tarsal bones. Patients with a flexible flatfoot and a tight tendo-Achilles should be treated with stretching exercises. Often patients are referred to physical therapy to ensure that they are stretching appropriately. For the few patients with persistent pain despite conservative measures, surgical correction of the flatfoot can be considered. This typically involves a lateral column lengthening, which addresses all components of the deformity. The procedure involves an osteotomy of the calcaneus, with placement of a trapezoidal bone graft. A lengthening of the tendo-Achilles is often required, sometimes with a plantarflexion osteotomy of the medial cuneiform if the first ray remains supinated or in varus to restore the tripod surface of the foot. This procedure preserves the mobility of the hindfoot joints, in contrast to a subtalar or triple arthrodesis. Although a hindfoot arthrodesis may correct the deformity adequately, the subsequent stress transfer to neighboring joints may result in late-onset, painful degenerative changes.

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715.6 Tarsal Coalition

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

Tarsal coalition, also known as **peroneal spastic flatfoot**, is characterized by a painful, rigid flatfoot deformity and peroneal (lateral calf) muscle spasm without true spasticity. It represents a congenital fusion or failure of segmentation between two or more tarsal bones. Any condition that alters the normal gliding and rotatory motion of the subtalar joint may produce the clinical appearance of a tarsal coalition. Thus



Fig. 715.6 Lateral weight-bearing radiograph demonstrating features of flatfoot.

congenital malformations, arthritis, inflammatory disorders, infection, neoplasms, and trauma can be possible causes.

The most common tarsal coalitions occur between the talus and calcaneus at the medial talocalcaneal facet (subtalar or talocalcaneal coalition) and between the calcaneus and navicular (calcaneonavicular coalition). Coalitions can be fibrous, cartilaginous, or osseous. Tarsal coalition occurs in approximately 1% of the general population and appears to be inherited as an autosomal dominant trait with nearly full penetrance. Approximately 60% of calcaneonavicular and 50% of medial facet talocalcaneal coalitions are bilateral.

CLINICAL MANIFESTATIONS

Approximately 25% of patients will become symptomatic, typically during the second decade of life. Although the flatfoot and a decrease in subtalar motion may have been present since early childhood, the onset of symptoms may correlate with the additional restriction in motion that occurs as a cartilaginous bar ossifies, reducing flexibility. Recurrent "ankle sprains" often accompany the presenting symptoms. The timing of ossification varies between the talonavicular (3–5 years of age), the calcaneonavicular (8–12 years of age), and the talocalcaneal (12–16 years of age) coalitions. Hindfoot pain is commonly observed, especially in the region of the sinus tarsi and under the head of the talus. Symptoms are activity related and are often increased with running or prolonged walking, especially on uneven surfaces. There may be tenderness over the site of the coalition and/or pain with testing of subtalar motion. The clinical appearance of a flatfoot is seen in both the weight-bearing and non-weight-bearing positions. There is a restriction in subtalar motion.

RADIOGRAPHIC EVALUATION

AP and lateral weight-bearing radiographs and an oblique radiograph of the foot should be obtained as well as a Harris or "heel" view (Table 715.1). A calcaneonavicular coalition is seen best on the oblique radiograph. On the lateral radiograph, there may be elongation of the anterior process of the calcaneus, known as the "anteater sign" (Fig. 715.7). A talocalcaneal coalition may be seen on a Harris (axial) view of the heel. On the lateral radiograph, there may be narrowing of the posterior facet of the subtalar joint or a C-shaped line along the medial outline of the talar dome and the inferior outline of the sustentaculum tali ("C sign"; Fig. 715.8). Beaking (or spur formation) of the anterior aspect of the talus on the lateral view is seen with some frequency and results from an alteration in the distribution of stress. Irregularity in the subchondral bony surfaces may be seen in patients with a cartilaginous coalition, in contrast to a well-formed bony bridge in those with an osseous coalition. A fibrous coalition may require additional imaging studies to diagnose. Although plain films may be diagnostic, a CT scan is considered the "gold standard" imaging modality when a coalition is suspected (see Fig. 715.8). In addition to securing the diagnosis, this study helps define the degree of joint involvement in patients with a talocalcaneal coalition. Although uncommon, more than one tarsal coalition may be observed in the same patient. MRI is also very accurate at detecting tarsal coalition, with a high rate of agreement with CT, and

Table 715.1 Radiographic Secondary Signs Associated with Tarsal Coalition

Talar beaking
Posterior subtalar facet narrowing
Rounding and flattening of the lateral talar process
Hypoplasia of the talus, shortening of the talar neck
Anterior nose sign
Ball-and-socket ankle joint
Continuous C-sign
Flatfoot deformity
Altered navicular morphology (wide or laterally tapering)
Dysmorphic sustentaculum tali (enlarged and ovoid on lateral radiograph)

From Slovis T, ed. *Caffey's Pediatric Diagnostic Imaging*, 11th ed. Philadelphia: Mosby; 2008: p. 2604.



Fig. 715.7 Calcaneonavicular coalition in a child with the anteater sign (arrow) and talar beak (dashed arrow). Elongation of the anterior calcaneus resembling the nose of an anteater is present. (From Kan JH, Laor T. Congenital anomalies of bone. In: Coley BD, ed. Caffey's Pediatric Diagnostic Imaging, 13th ed. Philadelphia: Elsevier; 2019: Fig. 131.11, p. 1250.)

may be useful when other diagnoses for pain are suspected and CT is diagnostically suboptimal, or in young children whose tarsal bones are not ossified. MRI offers less radiation exposure but requires more time and may necessitate sedation.

TREATMENT

The treatment of symptomatic tarsal coalitions varies according to the type and extent of coalition, the age of the patient, and the presence and magnitude of symptoms. Treatment is required only for symptomatic coalitions, and the initial management consists of activity restriction and nonsteroidal antiinflammatory medications, often with a shoe insert such as the UCBL orthosis. Immobilization in a short leg walking cast for 4–6 weeks may be required in patients with more pronounced symptoms or those who do not respond to initial measures. For patients with chronic pain despite an adequate trial of nonoperative therapy, surgical treatment should be considered as persistently symptomatic patients who are treated surgically are less likely to report persistent problems at long-term follow-up. Options include resection of the coalition, osteotomy, and/or, in extensive coalitions, arthrodesis. For the calcaneonavicular coalition, resection, and interposition of fat, bone wax, or of the extensor digitorum brevis muscle has been successful. Often, concomitant hindfoot valgus and contracture of the gastrocnemius-soleus are present. In these patients, more reliable pain relief can be obtained with resection of the coalition, correction of the hindfoot valgus by calcaneal lengthening osteotomy with bank bone graft and lengthening of the gastrocnemius-soleus complex. For those with extensive involvement of the joint and/or degenerative changes, a triple arthrodesis may be the best option; this is rarely needed in adolescents.

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715.7 Cavus Feet

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

Cavus is a deformity involving plantarflexion of the forefoot or midfoot on the hindfoot and may involve the entire forepart of the foot or just the medial column. The result is an elevation of the medial longitudinal arch (Fig. 715.9). A deformity of the hindfoot will often develop to compensate for the primary forefoot abnormality. Although familial cavus may occur, most patients with this deformity will have an underlying neuromuscular etiology. The initial goal is to rule out, and if present, treat, any underlying causes. These diagnoses may relate to abnormalities of the spinal cord (occult dysraphism, tethered cord, polio, myelodysplasia, etc.) and peripheral nerves (hereditary motor and sensory neuropathies [see Chapter 653], such as Charcot-Marie-Tooth [CMT] disease, Dejerine-Sottas disease, or

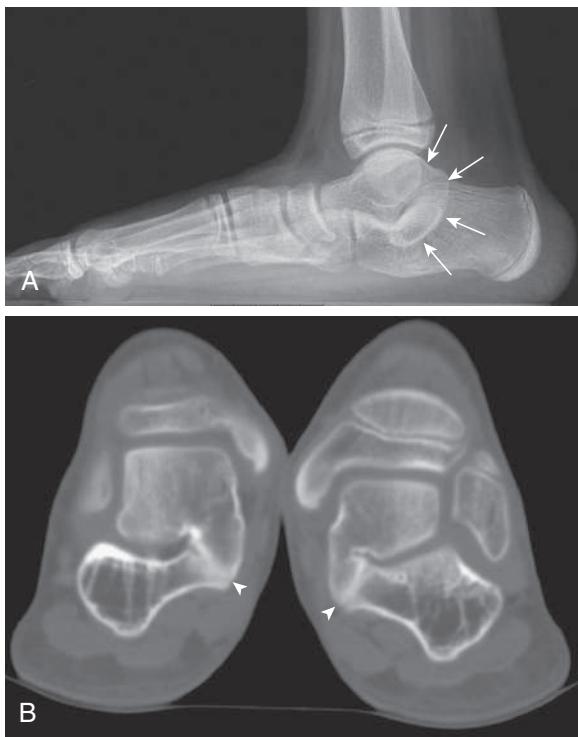


Fig. 715.8 Talocalcaneal coalition. A, A lateral radiograph demonstrates the C sign (arrows), ovoid, elongated sustentaculum tali, and pes planus. B, Computed tomography with coronal reformats in a different patient demonstrates bilateral middle facet subtalar coalitions (arrowheads). (From Laor T, Kan JH. Congenital anomalies of bone. In: Coley BD, ed. Caffey's Pediatric Diagnostic Imaging, 13th ed. Philadelphia: Elsevier; 2019: Fig. 131-13.)

Refsum disease). Although a unilateral cavus foot is most likely to result from an occult intraspinal anomaly, bilateral involvement usually suggests an underlying nerve or muscle disease. Cavus is commonly observed in association with a hindfoot deformity. Two thirds of patients with pes cavovarus have CMT, and conversely, 80% of CMT patients have pes cavovarus. In patients with hereditary motor and sensory neuropathies, progressive weakness and muscle imbalance result in plantarflexion of the first ray and medial column. To obtain a plantigrade foot, the hindfoot must roll into varus. With equinocavus, the hindfoot is in equinus, whereas in calcaneocavus (usually seen in polio or myelodysplasia), the hindfoot is in calcaneus (excessive dorsiflexion).

TREATMENT

Any underlying diagnosis must be identified, as this knowledge also helps address the specific disorder and formulate the proper management strategy. With mild deformities, stretching through physical therapy or serial casting of the plantar fascia and contracted muscles with exercises to strengthen weakened muscles may help delay progression. An ankle-foot orthosis may be necessary to stabilize the foot and improve ambulation. Surgical treatment is indicated for progressive or symptomatic deformities that have failed to respond to nonoperative measures or in the foot that is no longer braceable. The specific procedures recommended depend on the degree of deformity and the underlying diagnosis. In the case of a progressive neuromuscular condition, recurrence of deformity is commonly observed, and additional procedures may be required to maintain a plantigrade foot. Families should be counseled in detail regarding the disease process and the expected gains from the surgery. The goal of surgery is to restore motion and alignment, and to improve muscle balance. For milder deformities, a soft tissue release of the plantar fascia, often combined with a tendon transfer, may suffice. For patients with a fixed bony deformity of the forefoot, midfoot, and/or hindfoot, one or more osteotomies may be required for realignment. A triple arthrodesis (calcaneocuboid,



Fig. 715.9 Clinical picture demonstrating pes cavus.

talonavicular, and subtalar) may be required for severe or recurrent deformities in older patients. Long-term bracing is usually helpful in preventing recurrence.

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715.8 Osteochondroses/Apophysitis

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

Osteochondroses are idiopathic avascular necroses of bones, which may involve tarsal bones as well. Although rare, they may be observed in the tarsal navicular (**Köhler disease**) or the second or third metatarsal head (**Freiberg infarction**; Fig. 715.10). These are generally self-limited conditions that commonly result in activity-related pain, which can at times be disabling. The treatment is based on the degree of symptoms and most often includes restriction of activity. The diagnosis is made by history and physical examination in conjunction with concordant radiographic findings. The navicular is particularly sensitive, as it is the last tarsal bone to ossify, which may lead to compression from adjacent ossified bones. For patients with Köhler disease, nonsurgical treatment with a short leg cast or controlled ankle motion (CAM) boot for 6–8 weeks may provide significant relief. Patients with Freiberg infarction may benefit from a period of casting and/or shoe modifications such as a rocker-bottom sole, a stiff-soled shoe, or a metatarsal bar (not pads) to offload the forefoot. Degenerative changes and collapse of the metatarsal head will occasionally occur following the gradual healing process, and surgical intervention is required in a small subset of cases. Procedures have included joint debridement, bone grafting, redirection osteotomy, subtotal or complete excision of the metatarsal head, and joint replacement.

Apophysitis represents inflammation or stress injury to the areas on or around growth plates in children and adolescents from repetitive tensile loading and is most often observed during periods of rapid growth. Enthesopathy refers to injury or inflammation at attachment points of tendons to bones. Calcaneal apophysitis (**Sever disease**) is the most common cause of heel pain in children; treatment includes activity modification, nonsteroidal antiinflammatory medications, heel cord stretching exercises, and heel cushions or arch supports. **Iselin disease** represents an apophysitis at the fifth metatarsal base where the peroneus brevis attaches and is less common. Even though the mandate for imaging heel pain in all children remains controversial, radiographs should be considered when the symptoms are unilateral or fail to respond to treatment. Gentle stretching, a period of rest (6–8 weeks), and avoidance of sports will often resolve symptoms, although recurrence is common until maturity when the apophyses close.



Fig. 715.10 Radiographs of Köhler disease (A) and Freiberg infarction (B).

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715.9 Puncture Wounds of the Foot

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

Most puncture wound injuries to the foot may be adequately managed in the clinic or emergency department. Treatment involves a thorough irrigation and a tetanus booster, if appropriate, and many clinicians will recommend antibiotics. Using this approach, the majority will heal without complication. A subset of cases may develop cellulitis, most often caused by *Staphylococcus aureus*, and require intravenous antibiotics with or without surgical drainage if an abscess develops. Persistent signs of infection should be investigated more thoroughly. Deep infection is uncommon and may be associated with septic arthritis, infectious chondritis, or osteomyelitis. The most common organisms are *S. aureus* and *Pseudomonas aeruginosa*; the treatment involves a thorough surgical debridement followed by a short course (10–14 days) of systemic antibiotics. Although plain radiographs will demonstrate any metallic fragments or other radiopaque foreign bodies, ultrasonography (or CT or MRI) may be necessary to identify radiolucent objects such as glass, plastic, or wood. Routine empiric exploration and removal of foreign bodies is not required but may be necessary when symptoms are present or when an infection is suspected. Pain and/or gait disturbance is more likely with superficial objects under the plantar surface of the foot.

A special situation occurs when a puncture wound from a nail comes through a rubber sneaker or running shoe. This situation presents a high risk of a *Pseudomonas* infection, and consideration should be given to a thorough irrigation and debridement under general anesthesia followed by systemic antibiotics for 10–14 days. Foreign-body entrapment of rubber may also occur.

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715.10 Toe Deformities

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

JUVENILE HALLUX VALGUS (BUNION)

Juvenile hallux valgus is approximately 10-fold more common in females than in males. A family history is common and is typically associated with familial ligamentous laxity. The etiology is multifactorial, and important factors include genetic factors, ligamentous laxity, pes planus, wearing shoes with a narrow toe box, and occasionally spasticity (e.g., in the setting of cerebral palsy). Bunion refers to the

bump that occurs with chronic rubbing against the prominent first metatarsal head medially.

Clinical Manifestations

There is prominence of the first metatarsophalangeal (MTP) joint medially and often erythema and callus from chronic irritation (Fig. 715.11). The great toe metatarso-phalangeal joint is in valgus and is usually pronated. There is splaying (widening) of the forefoot. Pes planus, with or without an associated heel cord contracture, is also observed commonly. Although cosmesis is perhaps the most common concern, patients may have pain in the region of the first MTP joint and/or difficulty with shoe wear.

Radiographic Evaluation

Weight-bearing AP and lateral radiographs of the feet should be obtained. On the AP view, common measurements include the angular relationships between the first and second metatarsals (intermetatarsal angle, <10 degrees is normal) and between the first metatarsal and the proximal phalanx (hallux valgus angle, <25 degrees is normal) (see Fig. 715.11). The orientation of the first metatarsal-medial cuneiform joint is also documented. On the lateral radiograph, the angular relationship between the talus and the first metatarsal helps identify a midfoot break associated with pes planus. Radiographs are more helpful in surgical planning than in establishing the diagnosis.

Treatment

Conservative management of adolescent bunions consists primarily of shoe modifications. It is important that footwear accommodate the width of the forefoot, or pressure on the medial prominence can lead to callouses and pain. Patients should avoid wearing shoes with a narrow toe box and/or a high heel. Shoe modifications, such as a soft upper, bunion last, or heel cup, also may be recommended. In the presence of flexible pes planus, an orthotic to restore the medial longitudinal arch may be beneficial. If the flatfoot is rigid, further evaluation for tarsal coalition should be pursued. If a tendo-Achilles contracture is present, stretching exercises are recommended. The value of night splinting remains unproven. Surgical treatment is reserved for those patients with persistent and disabling pain who have failed a course of nonoperative therapy. Surgery is not advised



Fig. 715.11 Juvenile hallux valgus (bunion). A, Clinical appearance of the right foot of an 11-yr-old with hallux valgus. B, Radiograph shows an intermetatarsal angle of 15 degrees. The hallux valgus angle measures 42 degrees. It is the angle formed by a line drawn along the axis of the proximal phalanx and a second line drawn along the shaft of the first metatarsal. (From Ricco Al. Disorders of the foot. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier, 2022; Fig. 19-11.)

purely for cosmesis. Surgery is usually delayed until skeletal maturity to decrease the risk of either recurrence or overcorrection, although guided growth via hemiepiphiodesis in skeletally immature symptomatic patients is gaining popularity. Radiographs are essential in preoperative planning to assess both the magnitude of deformity (hallux valgus angle, intermetatarsal angle, distal metatarsal articular angle) and associated features such as obliquity of the first metatarsal-medial cuneiform joint. Surgical treatment often involves a soft tissue release and/or rebalancing procedure at the first MTP joint, and a single or double osteotomy of the first metatarsal to decrease foot width and realign the joints along the medial column of the forefoot. If there is deformity in the medial cuneiform, medial cuneiform opening wedge osteotomy and bone graft placement can correct the proximal alignment. An arthrodesis of the first MTP joint may be indicated in patients with spasticity to prevent recurrence.

CURLY TOES

Curly toes, or varus deformity, is caused by contracture of the flexor digitorum longus resulting in flexion at the MTP and interphalangeal (IP) joints and medial deviation of the toe. It is extremely common and is often seen in the parents of affected patients. The toe usually lies underneath its neighbor, and the third, fourth, and fifth toes are most commonly involved (Fig. 715.12). The deformity very rarely causes symptoms, and active treatment (stretching, splinting, or taping) is not required. Most cases improve over time, and a subset will resolve completely. For the rare case in which there is chronic pain or skin irritation, release of the flexor digitorum longus tendon at the distal IP joint may be considered. Osteotomy in the older child may rarely be considered.

OVERLAPPING FIFTH TOE

Congenital digitus minimus varus, or varus fifth toe, involves dorsiflexion and adduction of the fifth toe. The fifth toe typically overlaps the fourth. There is also a rotatory deformity of the toe, and the nail tends to point outward. Mild congenital shortness of the fifth metatarsal is common. The deformity is usually bilateral and may have a genetic basis. Symptoms are frequent and involve pain over the dorsum of the toe from shoe wear. Nonoperative treatment has not been successful. For symptomatic patients, several different options for reconstruction have been described. Common features of operative intervention include releasing the contracted extensor tendon and the MTP joint capsule (dorsal, dorsomedial, or complete), and plastic alteration of the tight skin. An alternative procedure involves creation of a syndactyly between the fourth and fifth toes.

POLYDACTYLY

Polydactyly is the most common congenital toe deformity and is seen in approximately 2 in every 1,000 births; it is bilateral in 50% of cases. Polydactyly may be preaxial (great toe) or postaxial (fifth toe), and occasionally one of the central toes is duplicated. Associated anomalies are found in approximately 10% of postaxial and 20% of preaxial polydactyly and may be present in over half of patients with more rare forms of polydactyly. One third of patients will also have polydactyly of the hand. Conditions that may be associated with polydactyly include Ellis-Van Creveld (chondroectodermal dysplasia), longitudinal deficiency of the tibia, and Down syndrome. The extra digit may be either rudimentary or well formed, and plain radiographs of the foot help define the anatomy and evaluate any coexisting bony anomalies. Treatment is indicated for cosmesis and to allow for fitting with standard shoes. This involves surgical removal of the extra digit, and the procedure is generally performed between 9 and 12 months of age. Rudimentary digits may be surgically excised earlier but should not be "tied off," as this may leave painful residual scars or bone masses. For surgical treatment, radiographic evaluation is critical to properly plan reconstruction for a properly shaped and stable foot at maturity.



Fig. 715.12 Curly third, fourth, and fifth toes. (From Ricco Al. Disorders of the foot. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022. Fig. 19-133.)



Fig. 715.13 Clinical picture of polysyndactyly involving the great toe.

SYNDACTYLY

Syndactyly involves webbing of the toes, which may be simple (soft tissue only) or complex (involving bone). The syndactyly may be incomplete or complete (extends to the tip of the toes), and the toenails may be confluent. There is often a positive family history, and the third and fourth toes are most frequently involved. Symptoms are extremely rare, and cosmetic concerns are infrequent. Treatment is only required for a subset of cases in which there is an associated polydactyly (Fig. 715.13). Complex syndactyly may be seen in patients with Apert syndrome.

HAMMER TOE

A hammer toe is a flexion deformity of the lesser toes that involves the proximal IP (PIP) joint. This deformity may be distinguished from a curly toe by the absence of rotation. The second toe is most often involved, and a painful callus may develop over the dorsum of the toe where it rubs on the shoe or the tip of the toe which is directed against the sole of the shoe. Nonoperative therapy is rarely successful, and surgery is recommended for symptomatic cases. A release of the flexor tendons will suffice in most cases. Some authors recommend a transfer of the flexor tendon to the extensor tendon. For severe cases with significant rigidity, especially in older patients, a partial or complete resection of the proximal phalanx and a PIP joint fusion may be required.

MALLET TOE

Mallet toe involves a flexion contracture at the distal IP (DIP) joint and results from congenital shortening of the flexor digitorum longus tendon. Patients may develop a painful callus on the plantar surface of the tuft or dorsal aspect of the DIP joint. As nonoperative therapy is usually unsuccessful, surgery is required for patients with chronic symptoms. For flexible deformities in younger children, stretching or release of the flexor digitorum longus tendon is recommended. For stiffer deformities in older patients, resection of the head of the middle phalanx, or arthrodesis of the DIP joint, may be considered.

CLAW TOE

A claw toe deformity involves hyperextension at the MTP joint and flexion at both the PIP and DIP joints, often associated with dorsal subluxation of the MTP joint. *This condition must be distinguished from hyperextension of the MTP joint due to ground reaction where the stiff flexed toe in stance pushes the MTP joint into hyperextension. If the MTP does hyperextend, this is a claw toe.* The majority are associated with an underlying neurologic disorder and must be evaluated. The etiology is usually muscle imbalance, and the extensor tendons are recruited to substitute for weakening of the tibialis anterior muscle. If treatment is elected, surgery is required. Transfer of the extensor digitorum (or hallucis) tendon to the metatarsal neck is commonly performed along with a dorsal capsulotomy of the MTP joint and fusion of the PIP joint (IP joint of the great toe).

ANNULAR BANDS

Bands of amniotic tissue associated with amniotic disruption syndrome (early amniotic rupture sequence, congenital constriction band

syndrome, annular band syndrome) may become entwined along the extremities, resulting in a spectrum of problems from in utero amputation (Fig. 715.14) to a constriction ring along a digit (Fig. 715.15; see Chapter 100). These rings, if deep enough, may result in impairment of arterial or venous blood flow as well as severe damage to the muscles, tendons, and bone growth distal to the band. Even though concerns regarding tissue viability are less common, swelling from impairment in venous return is often an urgent problem. The treatment of annular bands usually involves observation; however, circumferential release of the band may be required emergently if arterial inflow is obstructed or electively to relieve venous congestion. Physical therapy and bracing may help prevent future contractures and deformities.

MACRODACTYLY

Macrodactyly represents an enlargement of the toes and may occur as an isolated problem or in association with a variety of other conditions such as Proteus syndrome (Fig. 715.16), neurofibromatosis, tuberous sclerosis, and Klippel-Trenaunay-Weber syndrome. This condition results from a deregulation of growth, and there is hyperplasia of one or more of the underlying tissues (osseous, nervous, lymphatic, vascular, fibrofatty). Macrodactyly of the toes may be seen in isolation (localized gigantism) or with enlargement of the entire foot or leg. In addition to cosmetic concerns, patients may have difficulty wearing standard shoes. The initial treatment is observation, if possible. This is a difficult condition to treat surgically, and complications are frequent. For involvement of a single toe, the best option may be a resection of the ray (including the metatarsal). For greater degrees of involvement, debulking of the various tissues is required. Often a growth arrest of the underlying osseous structures is performed. Stiffness and wound problems are common. The rate of recurrence is high, and more than one debulking may be required. Patients may elect to have an amputation if the process cannot be controlled by less extensive procedures. Leg length inequality is common and must be looked for and treated if needed.

SUBUNGUAL EXOSTOSIS

A subungual exostosis is a benign bone mass that projects out from the dorsal and medial surface of a distal toe phalanx, under the nail. The etiology is unknown but may relate to minor, repetitive trauma. The great toe is involved most often. Patients present with discomfort, and the toenail may be deformed and elevated. The lesion may be demonstrated on plain radiographs and histologically involves normal bone with a fibrocartilaginous cap. The treatment for symptomatic lesions is excision, and the recurrence rate is approximately 10%.

INGROWN TOENAIL

Ingrown toenails are relatively common in infants and young children and usually involve the medial and/or lateral border of the great toe. Symptoms include chronic irritation and discomfort. Recurrent infection is seen in some cases. Parents should be instructed when cutting toenails to cut straight across the distal aspect of the nail, rather than



Fig. 715.14 Constriction band syndrome with congenital amputation.



Fig. 715.15 Constriction band syndrome with foot involvement.



Fig. 715.16 Macrodactyly of the great toe in a case of Proteus syndrome.

curve inward at the nail edges. If conservative measures, including shoe modifications, warm soaks, and appropriate nail trimming fail to control the symptoms, surgical removal of a portion of the nail should be considered.

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AGE GROUP	DIAGNOSTIC CONSIDERATIONS
0-6yr	Poorly fitting shoes Fracture Puncture wound Foreign body Osteomyelitis Cellulitis Juvenile idiopathic arthritis Hair tourniquet Dactylitis Leukemia
6-12yr	Poorly fitting shoes Trauma (fracture, sprain) Juvenile idiopathic arthritis (enthesopathy) Puncture wound Sever disease (calcaneal apophysitis) Accessory tarsal navicular bone Hypermobile flatfoot Tarsal coalition Oncologic (Ewing sarcoma, leukemia)
12-18yr	Poorly fitting shoes Stress fracture Trauma (fracture, sprain) Foreign body Ingrown toenail Metatarsalgia Plantar fasciitis Achilles tendinopathy Accessory ossicles (navicular, os trigonum) Tarsal coalition Avascular necrosis of metatarsal (Freiberg infarction) or navicular (Köhler disease) bones Plantar warts

From Marcdante KJ, Kliegman RM, Schuh AM. *Nelson Essentials of Pediatrics*, 9th ed. Philadelphia: Elsevier; 2023.

715.11 Painful Foot

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

Table 715.2 shows a differential diagnosis for foot pain in different age ranges. In addition to the history and physical examination, plain radiographs are most helpful in establishing the diagnosis. Occasionally more sophisticated imaging modalities such as CT or MRI will be required.

715.12 Shoes

Christine M. Goodbody, Jennifer J. Winell, and Richard S. Davidson

In toddlers and children, a well-fitting shoe with flexible soles is recommended. This recommendation is in part based on studies suggesting that the development of the longitudinal arch seems to be best in societies in which shoes are not worn, and flatfeet are more common in shod children. Well-cushioned, shock-absorbing shoes are helpful in the child and adolescent athlete to decrease the chances of developing an overuse injury. Otherwise, shoe modifications are generally reserved for abnormalities in either alignment between segments of the foot or symptoms from an underlying condition (e.g., a limb-length discrepancy). Numerous modifications are available.

As a rule, shoes protect the foot from abnormal temperature as well as rough surfaces and sharp objects but have not been shown to help the normal foot develop. Poorly fitting shoes may create problems.

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Chapter 716

Torsional and Angular Deformities of the Limb

Brendan A. Williams, Jennifer J. Winell,
and Lawrence Wells

716.1 Normal Limb Development

Brendan A. Williams, Jennifer J. Winell, and
Lawrence Wells

During the seventh week of intrauterine life, the lower limb rotates medially to bring the great toe toward the midline. The hip joint forms by the eleventh week; the proximal femur and acetabulum continue to develop until physeal closure in adolescence. The first component of rotation is the femoral neck, which is rotated approximately 40 degrees anteriorly at birth. This anterior rotation is referred to as **anteversion** (the angle between the axis of the femoral neck and the transcondylar axis). The increased anteversion results in increased internal rotation of the hip. In most children, femoral anteversion decreases to 15–20 degrees by 8–10 years of age. Conditions such as cerebral palsy that involve spasticity of the lower extremities can result in the persistence of fetal anteversion. This results in torsional abnormalities of the lower limb and gait disturbances. The second component of limb rotation is found in the tibia. Tibial torsion is the angular difference between the axis of the knee and the transmalleolar axis. Infants can have 30 degrees of medial rotation of the tibia. When skeletally mature, the rotation is between 5 degrees of medial rotation and 15 degrees of lateral rotation (Fig. 716.1). Excessive medial rotation of the tibia is referred to as **medial tibial torsion**. This is very common and, although concerning to parents, very rarely requires treatment. The medial or lateral rotation beyond ± 2 SDs from the mean is considered abnormal rotation. The third component of rotational (axial) abnormalities of the lower extremity derives from the foot. Metatarsus adductus can cause the foot to curve medially, pointing the toes inward. It is assessed by observing the medial and lateral borders of the foot.

Torsional deformity may be simple, involving a single component, or complex, involving multiple components. Complex deformities may be additive (internal tibial torsion and internal femoral torsion are additive) or compensatory (external tibial torsion and internal femoral torsion are compensatory).

The normal tibiofemoral angle at birth is 10–15 degrees of physiologic varus. The alignment changes to 0 degrees by 18 months, and physiologic valgus up to 12 degrees is reached in between 3 and 4 years of age. The normal valgus of 7 degrees is achieved by 5–8 years of age (Fig. 716.2). Persistence of varus beyond 2 years of age may be pathologic and is seen in conditions such as Blount disease. Overall, 95% of developmental physiologic genu varum and genu valgum cases resolve with growth. Persistent genu valgum or valgus into adolescence is considered pathologic and deserves further evaluation.

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716.2 Limb Evaluation

Brendan A. Williams, Jennifer J. Winell, and
Lawrence Wells

When evaluating concerns regarding the limb, the provider should obtain a history documenting onset, progression, functional limitations, previous treatment, evidence of neuromuscular disorder, and any significant family history. The examination should assess the exact

torsional profile and include (1) foot progression angle, (2) femoral anteversion, (3) tibial version with thigh-foot angle, and (4) assessment of foot adduction and abduction.

FOOT PROGRESSION ANGLE

Limb position during gait is expressed as the **foot progression angle** and represents the angular difference between the axis of the foot with the direction in which the child is walking. Its value is usually estimated by asking the child to walk in the clinic hallway (Fig. 716.3). Inward rotation of the foot is assigned a negative value, and outward rotation is designated with a positive value. The normal foot progression angle in children and adolescents is 10 degrees (range: –5 to 20 degrees). The foot progression angle delineates whether there is an in-toeing or out-toeing gait.

FEMORAL ANTEVERSION

Hip rotation is measured with the child in the prone position, the hip in neutral flexion or extension, thighs together, and the knees flexed to 90 degrees (Fig. 716.4). Both hips are assessed at the same time. Internal rotation of the hip is measured by rotating the leg ipsilaterally, and external rotation is measured by rotating the leg contralaterally. Excessive anteversion has increased internal rotation, whereas retroversion has increased external rotation. The amount of anteversion can be approximately estimated by palpating the greater trochanter of the hip while internally rotating the limb. Femoral anteversion should be measured at the point when the greater trochanter is most prominent laterally during this rotation (Craig test).

TIBIAL ROTATION

Tibial rotation is measured using the **transmalleolar angle**. The transmalleolar angle is the angle between the longitudinal axis of the thigh with a line perpendicular to the axis of the medial and lateral malleolus (Fig. 716.5). In the absence of foot deformity, the **thigh-foot angle** is preferred (Fig. 716.6). It is measured with the child lying prone. The angle is formed between the longitudinal axis of the thigh and the longitudinal axis of the foot. It measures the tibial and hindfoot rotational status. Inward rotation is assigned a negative value, and outward rotation is assigned a positive value. Inward rotation indicates medial tibial torsion, whereas outward rotation represents lateral tibial torsion. Infants have a mean angle of –5 degrees (range: –35 to 40 degrees) as a consequence of normal in utero position. In mid-childhood through adult life, the mean thigh-foot angle is 10 degrees (range: –5 to 30 degrees).

FOOT SHAPE AND POSITION

The foot is observed for any deformities in prone and standing position. The **heel bisector line** (HBL) is used to evaluate the foot adduction and abduction deformities. The HBL is a line that divides the heel in two equal halves along the longitudinal axis (Fig. 716.7). It normally extends through the center of the second toe. When the HBL points medial to the second toe, the forefoot is abducted, and when the HBL is lateral to the second toe, the forefoot is adducted. Other lower-extremity problems, such as heel varus or valgus, can make assessment of axial plane issues more difficult.

It is also important to screen children with these foot deformities for associated hip dysplasia and neuromuscular problems (e.g., cerebral palsy).

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716.3 Torsional Deformities

Brendan A. Williams, Jennifer J. Winell, and
Lawrence Wells

FEMORAL ANTEVERSION

In-toeing gait most commonly results from excessive femoral anteversion. It occurs more commonly in females than males (2:1) in children 3–6 years of age and is congenital, resulting from persistent infantile

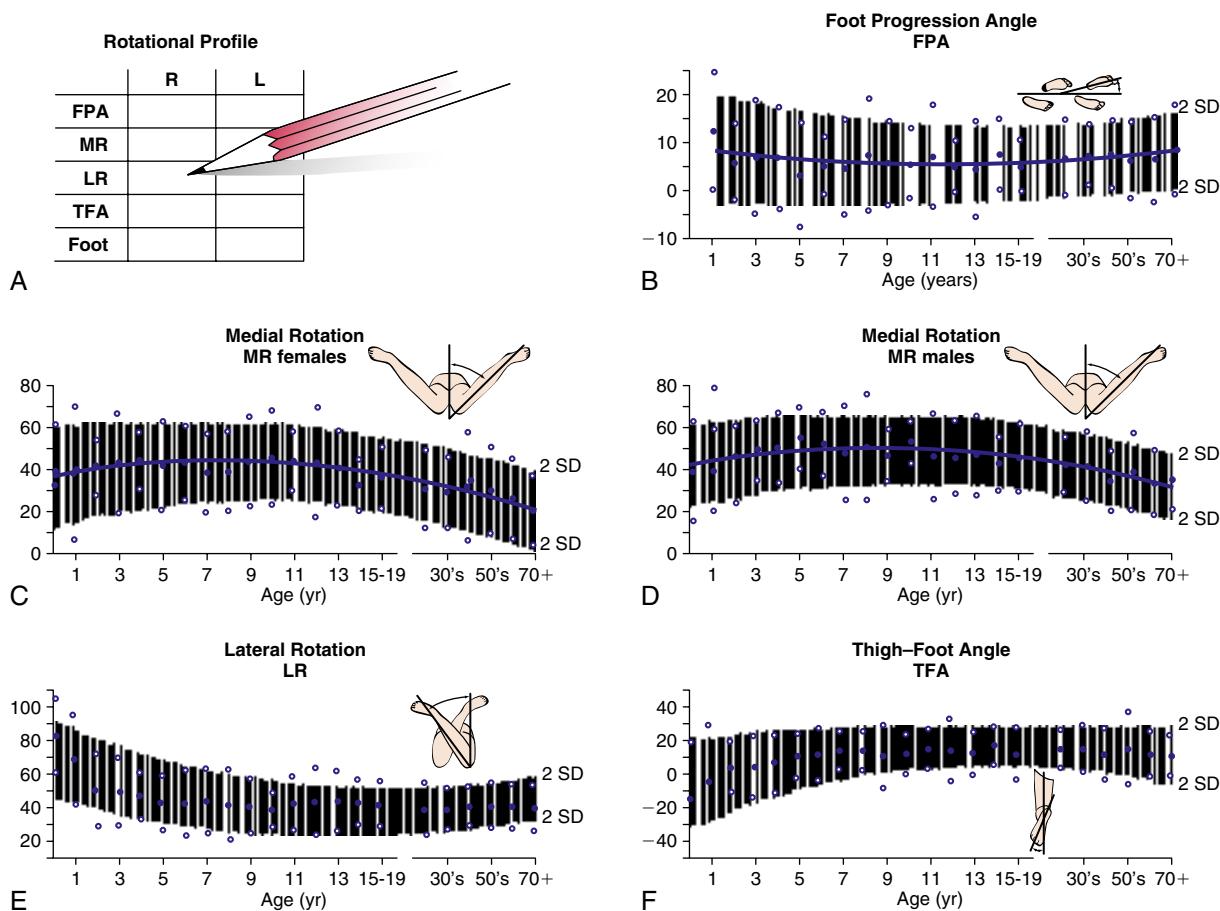


Fig. 716.1 A-F, The rotational profile from birth to maturity is depicted graphically. All graphs include 2 SD from the mean for the foot progression angle (FPA) for femoral medial rotation (MR) and lateral rotation (LR) (for males and females), and the thigh-foot angle (TFA). (From Morrissey RT, Weinstein SL, eds. Lovell and Winter's Pediatric Orthopaedics, 3rd ed. Philadelphia: Lippincott Williams & Wilkins; 1990.)

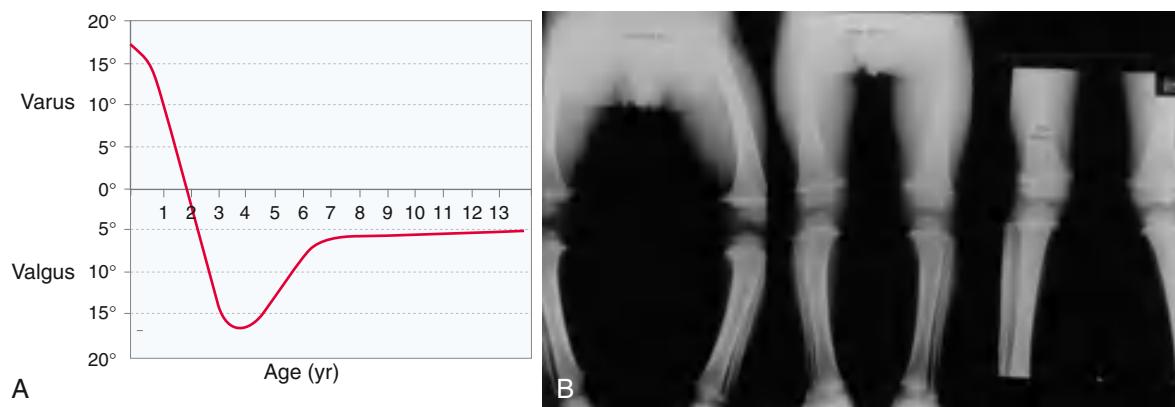


Fig. 716.2 A, Development of the tibiofemoral angle during growth (after Salenius). B, Serial radiographs demonstrating normal transition from varus alignment at 14 months to neutral position at 25 months to valgus tibiofemoral alignment at 39 months. (From Wimberly RL. Disorders of the leg. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig 18.13.)

anteversion. On examination, many children with this condition will have **generalized ligamentous laxity**. Gait examination reveals that the entire leg is inwardly rotated. Internal hip rotation is increased beyond 70 degrees, and consequently the external rotation is restricted to 10–20 degrees. Clinically, the patellae point inward when the foot is straight, and compensatory external rotation of the tibia is demonstrated. This is frequently mistaken as “genu valgum.” The amount of anteversion can be roughly estimated by palpating the greater trochanter of the hip

while internally rotating the limb. The point of maximal prominence of the greater trochanter laterally during this rotation corresponds to the degree of femoral anteversion.

Diagnosis is made clinically on examination; CT can provide objective measurements but is rarely indicated. The treatment is predominantly observation and reassurance. The torsion usually corrects with longitudinal growth by 8–10 years of age. Although rare, persistent deformity, unacceptable cosmesis, functional impairment, anteversion

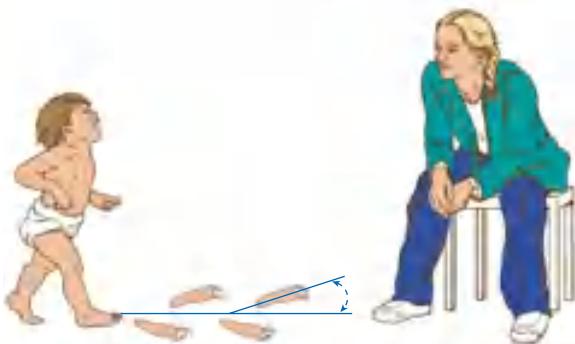


Fig. 716.3 Foot progression angle. The long axis of the foot is compared with the direction in which the child is walking. If the long axis of the foot is directed outward, the angle is positive. If the foot is directed inward, the angle is negative and indicates in-toeing. (From Thompson GH. Gait disturbances. In: Kliegman RM, ed. Practical Strategies in Pediatric Diagnosis and Therapy. Philadelphia: WB Saunders; 2004.)



A



B

Fig. 716.4 Anteversion measured by medial rotation of hip (A) and lateral rotation of hip (B). In this patient, internal rotation is nearly 90 degrees, suggestive of excessive femoral anteversion.

>45 degrees, and no external rotation beyond neutral are indications for operative intervention. Surgery involves a derotation osteotomy of the femur.

MEDIAL TIBIAL TORSION

Medial (internal) tibial torsion manifests with **in-toeing gait**. It is commonly associated with metatarsus adductus, genu valgum, or femoral anteversion. This condition is usually seen during the second year of life. It is often noticed after the child begins to walk independently. Many parents are concerned with a “bowed” appearance of the legs. Normally at birth, the medial malleolus lies behind the lateral



Fig. 716.5 Measurement of transmalleolar angle (TMA). (From Guler O, Isyar M, Karataş D, et al. Investigating the relationship between internal tibial torsion and medial collateral ligament injury in patients undergoing knee arthroscopy due to tears in the posterior one third of the medial meniscus. *Knee*. 2016;23(4):655–658, Fig 2.)

malleolus, but by adulthood, it is reversed, with the tibia in 15 degrees of external rotation. The treatment is observation and reassurance because spontaneous resolution with normal growth and development can be anticipated. Correction can be seen as early as 4 years of age and in some children by 8–10 years of age. Persistent deformity with functional impairment is treated with supramalleolar derotation osteotomy, but this is rarely necessary.

EXTERNAL FEMORAL TORSION

Femoral retroversion, when of idiopathic origin, is usually bilateral. The disorder is associated with an **out-toeing gait** and increased incidence of degenerative arthritis. The clinical examination of external femoral torsion shows excessive hip external rotation and limitation of internal rotation. The hip will externally rotate up to 70–90 degrees and internally rotate to only 0–20 degrees. External femoral torsion can also follow a **slipped capital femoral epiphysis (SCFE)**. There should be a low threshold to perform radiographs of the hips in children older than 10 years of age who present with hip or knee pain and decreased internal rotation of the hip on clinical examination. If a SCFE is detected, it is treated surgically. Occasionally, persistent femoral retroversion after SCFE can produce functional impairment resulting in a severe out-toed gait and difficulty opposing one's knees in the sitting position. The latter can be disabling to adolescent females. Should this occur, a Southwick osteotomy or surgical realignment might be necessary.

LATERAL TIBIAL TORSION

Lateral (external) tibial torsion is less common than medial rotation and is often associated with a **calcaneovalgus foot**. It can be compensatory to persistent femoral anteversion or secondary to a tight iliotibial band. Natural growth rotates the tibia externally, and therefore external tibial torsion can become worse with time. Clinically, the patella faces outward when the foot is straight. The thigh-foot angle and the transmalleolar angle are increased. There may be associated patellofemoral instability with knee pain. Although some correction can occur with growth, extremely symptomatic children may need a supramalleolar osteotomy, which is usually done by 10–12 years of age.

Fig. 716.6 Thigh-foot angle. With the child in the prone position and the knees flexed and approximated, the long axis of the foot can be compared with the long axis of the thigh. The long axis of the foot bisects the heel and the third or middle toe. A, External tibial torsion produces excessive outward rotation. B, Normal alignment is characterized by slight external rotation. C, Internal tibial torsion produces inward rotation. (From Zolkoske AC, Fehr SD. Gait disturbances. In: Kliegman RM, Toth H, Bordini BJ, Basel D, eds. Nelson Pediatric Symptom-Based Diagnosis, 2nd ed. Philadelphia: Elsevier; 2023: Fig 45.6.)

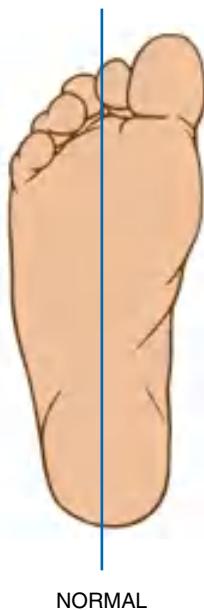
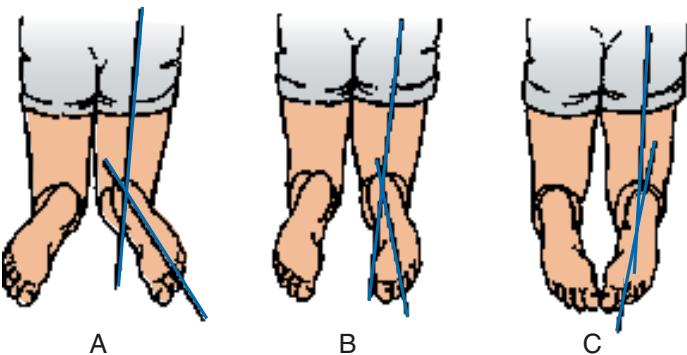


Fig. 716.7 Schematic demonstration of heel bisector line.

METATARSUS ADDUCTUS

Metatarsus adductus (see Chapter 715.1) manifests with forefoot adduction and medial rotation of all metatarsals. Of children with metatarsus adductus, 10–15% have hip dysplasia. The prognosis is good because the majority get better with nonoperative intervention. Feet that correct actively with stimulation of the lateral border of the foot are treated with stretching exercises alone. Feet that are flexible and correctable to neutral with manipulation are treated with stretching, reverse last shoes, or serial casting. Feet that do not correct fully with conservative care or rigid deformities are treated with medial capsulotomy of the first metatarsal cuneiform joint and soft tissue release by 2 years of age. Osteotomies of the base of the metatarsal may be performed after 6 years of age.

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716.4 Coronal Plane Deformities

Brendan A. Williams, Jennifer J. Winell, and Lawrence Wells

Genu varum and genu valgum are common pediatric deformities of the knee. Figure 716.2 presents the age-appropriate normal values for knee angle. Tibial bowing is common during the first year, bowlegs are common during the second year, and knock-knees are most prominent between 3 and 4 years of age.

GENU VARUM

Physiologic bowleg is a common torsional combination that is secondary to normal in utero positioning (Fig. 716.8). Spontaneous resolution with normal growth and development can be anticipated. Persistence of varus beyond 2 years of age may be pathologic. Causes of pathologic bowing include metabolic bone disease (vitamin D deficiency, rickets, hypophosphatasia), asymmetric growth arrest (trauma, infection, tumor, Blount disease), bone dysplasia (dwarfism, metaphyseal dysplasia), and congenital and neuromuscular disorders (Table 716.1). It is important to differentiate physiologic bowing from Blount disease (Table 716.2). Physiologic bowing should also be differentiated from rickets and skeletal dysplasia. Rickets has classic bony changes seen on plain radiographs with trumpeting widening and fraying of the metaphysis along with widening of the physis (see Chapter 69).

TIBIA VARA

Idiopathic tibia vara, or **Blount disease**, is a developmental deformity resulting from abnormal endochondral ossification of the medial aspect of the proximal tibial physis leading to varus angulation and medial rotation of the tibia (Fig. 716.9). The incidence is greater in Black patients and in overweight toddlers. It is also higher in patients who have an affected family member or started walking early in life. Idiopathic tibia vara has been classified into three types, depending on the age at onset: infantile (1–3 years of age), juvenile (4–10 years of age), and adolescent (11 years or older). The juvenile and adolescent forms are commonly combined as late-onset tibia vara. The exact cause of tibia vara remains unknown, although it is thought to result from abnormal growth of the physis due to excessive weight.

The **infantile** form of tibia vara is the most common. There is a predominance in Black females. Approximately 80% are bilateral with a prominent medial metaphyseal beak, internal tibial torsion, and leg-length discrepancy. The characteristics of the **juvenile** and **adolescent** (late-onset) forms include predominance in Black males, obesity, normal or greater than normal height, less frequent bilateral involvement (approximately 50%), slowly progressive genu varum deformity, pain rather than deformity as the primary initial complaint, no palpable proximal medial metaphyseal beak, minimal internal tibial torsion, mild medial collateral ligament laxity, and mild lower extremity length discrepancy. The infantile group has the greatest potential for progression.

An anteroposterior (AP) standing radiograph of both lower extremities with patellae facing forward and a lateral radiograph of the involved extremity should be obtained (Fig. 716.10). Weight-bearing radiographs are preferred and allow maximal presentation of the clinical deformity. The metaphyseal-diaphyseal angle (Drennan angle) can be measured and is useful in distinguishing between physiologic genu varum and early tibia vara (Fig. 716.11). This angle can aid in predicting the risk of progression. Angles greater than 16 degrees carry an increased risk of progression, whereas those less than 10 degrees are likely to resolve spontaneously. Patients with Drennan angles of 11–16 degrees should be monitored for progressive tibia vara.

The Langenskiöld classification, which describes six stages on radiographs for infantile Blount disease (Fig. 716.12), is the most widely

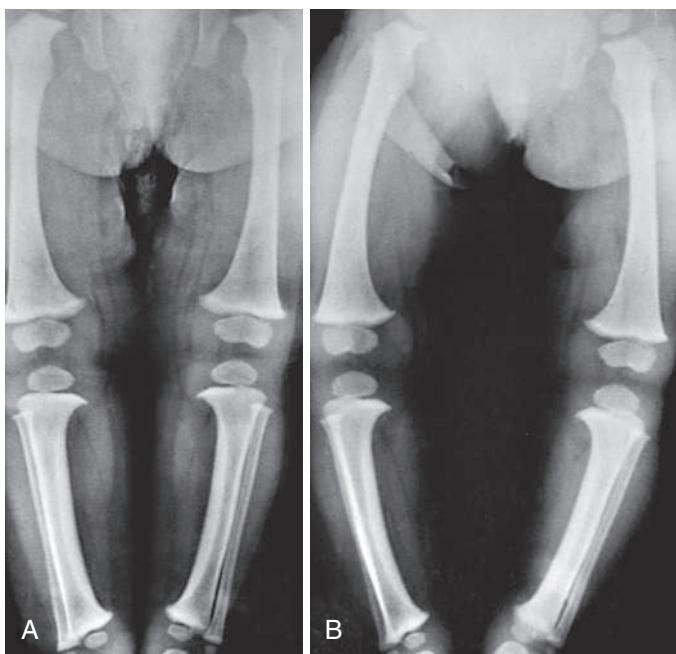


Fig. 716.8 Genu varum. A, In recumbent position, tibia and femora are bowed, but the legs do not appear bowed. B, In erect position during weight bearing and with ankles in apposition, the legs are bowed. (From Coley BD, ed. Caffey's Pediatric Diagnostic Imaging, 13th ed. Philadelphia: Elsevier; 2019.)

Table 716.1 Classification of Genu Varum (Bowlegs)

PHYSIOLOGIC

Asymmetric growth
Tibia vara (Blount disease)

- Infantile
- Juvenile
- Adolescent

Focal fibrocartilaginous dysplasia

Physeal injury

Trauma

Infection

Tumor

METABOLIC DISORDERS

Vitamin D deficiency (nutritional rickets)

Vitamin D-resistant rickets

Hypophosphatasia

SKELETAL DYSPLASIA

Metaphyseal dysplasia

Achondroplasia

Enchondromatosis

Modified from Thompson GH. Angular deformities of the lower extremities. In: Chapman MW, ed. Operative Orthopedics, 2nd ed. Philadelphia: JB Lippincott; 1993: Table 222-1, p. 3132.

Table 716.2 Differentiation of Leg Bowing

PHYSIOLOGIC BOWING	BLOUNT DISEASE
Gentle and symmetric deformity	Asymmetric, abrupt, and sharp angulation
Metaphyseal-diaphyseal angle <11 degrees	Metaphyseal-diaphyseal angle >11 degrees
Normal appearance of the proximal tibial growth plate	Medial sloping of the epiphysis Widening of the physis Fragmentation of the metaphysis
No significant lateral thrust	Significant lateral thrust

cited classification system, although other radiographic and MRI-based systems have been described. Langenskiöld differentiates based on fragmentation of the epiphysis, beaking of the medial tibial epiphysis, depression of the medial tibial plateau, and formation of a bony bar. CT with three-dimensional reconstructions and MRI can also be useful to assess the meniscus; the articular surface of the proximal tibia, including the posteromedial slope; or the integrity of the proximal tibial physis.

Management is based on the stage of the disease, the age of the child, and the nature of presentation (primary or recurrent deformity). In children younger than 3 years and Langenskiöld stage <3, bracing is effective and can prevent progression in 50% of patients. A maximal trial of 1 year of orthotic management is recommended. If complete correction is not obtained after 1 year or if progression occurs during this time, a corrective osteotomy is indicated. Surgical treatment is also indicated in children >4 years of age, those at Langenskiöld stage >3, and those with severe deformities. A proximal tibial valgus osteotomy and associated fibular diaphyseal osteotomy are usually the procedures of choice. In late-onset tibia vara, correction is also necessary to restore the mechanical axis of the knee. Hemiplateau elevation with correction of posteromedial slope has been established as a treatment modality in relapsed cases.

GENU VALGUM (KNOCK-KNEES)

The appearance of symmetric bilateral genu valgum most pronounced around age 4 years of age is part of the normal physiologic process of leg development. However, variation of up to 15 degrees of valgus is possible until 6 years of age. The majority of physiologic valgus has a good chance of correction until this age. The intermalleolar distance with the knees approximated is normally <2 cm, and in a severe valgus deformity, it could measure >10 cm. Pathologic conditions leading to valgus are metabolic bone disease (e.g., rickets or renal osteodystrophy), skeletal dysplasia, posttraumatic physeal arrest, tumors, and infection. The increased valgus at the knee causes lateral deviation of the mechanical axis with stretching of the medial aspect of the knee leading to knee pain. Deformities >15 degrees and occurring after 6 years of age are unlikely to correct with growth and require surgical management. In the skeletally immature, medial tibial epiphyseal hemiepiphiodesis or stapling (guided growth) is attempted for correction. In the skeletally mature, osteotomy is necessary at the center of rotation of angulation and is usually situated in the distal femur. Long-length AP radiographs of the leg in a weight-bearing stance are necessary for preoperative planning.

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716.5 Congenital Angular Deformities of the Tibia and Fibula

Brendan A. Williams, Jennifer J. Winell, and Lawrence Wells

POSTEROMEDIAL TIBIAL BOWING

Congenital posteromedial bowing is typically associated with a calcaneovalgus foot and rarely with secondary valgus of the tibia. The exact cause is unknown. Early operative intervention is not indicated because this bowing generally corrects with growth. However, despite the correction of angulation, there can be residual shortening in the tibia and fibula. The mean growth inhibition is 12–13% (range: 5–27%). The mean leg length discrepancy at maturity is 4 cm (range: 3–7 cm). The diagnosis of bowing is confirmed on radiographs, which show the posteromedial angulation without any other osseous abnormalities. The calcaneovalgus deformity of the foot improves with stretching or modified shoe wear and occasionally ankle-foot orthosis. Predicted leg length discrepancy <4 cm is managed with age-appropriate epiphysiodesis of the normal leg. Leg length discrepancy >4 cm is managed with combination of contralateral epiphysiodesis and ipsilateral lengthening. A corrective osteotomy for distal valgus may be required and can be done in the same setting while correcting leg length discrepancy.

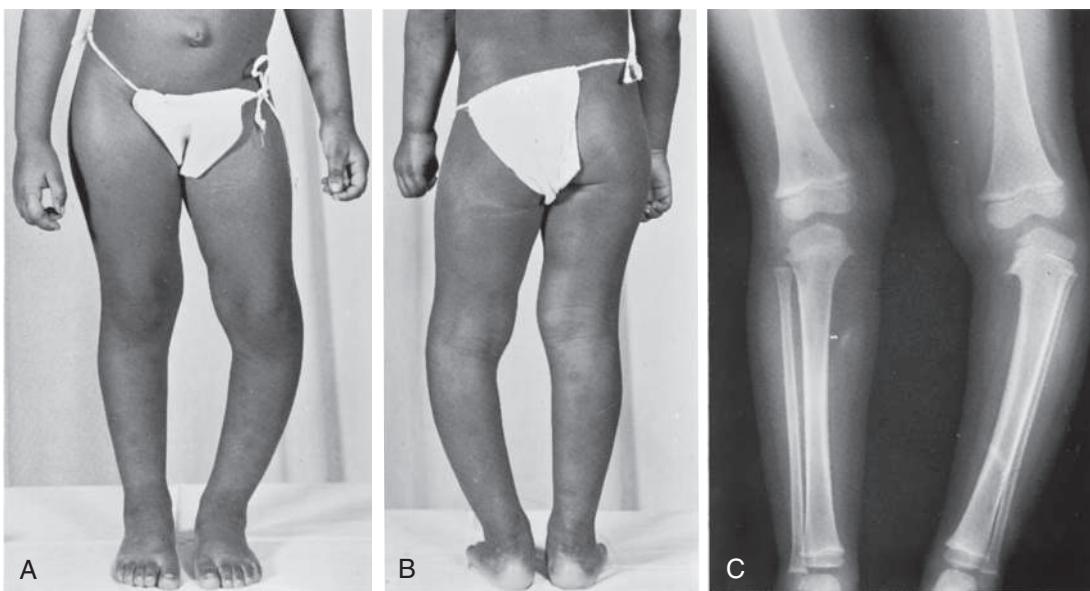


Fig. 716.9 Blount disease in a 5-year-old child. A and B, Preoperative clinical appearance. Note the abrupt medial deviation of the tibia just below the knee. Lateral “thrust” of the knee during weight bearing exacerbates the “limp.” C, Radiograph demonstrating abrupt angulation at the epiphyseal-metaphyseal junction and medial metaphyseal radiolucency and beaking with apparent lateral subluxation of the proximal end of the tibia. (From Johnston CE, Young M. Disorders of the leg. In: Herring JA, ed. Tachdjian’s Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig 18.14.)



Fig. 716.10 Anteroposterior radiograph of both knees in Blount disease.

ANTEROMEDIAL TIBIAL BOWING (POSTAXIAL HEMIMELIA)

Fibular hemimelia is the most common cause of anteromedial bowing of the tibia. The fibular deficiency can occur with complete absence of fibula or with partial fibular development both proximally and distally. It is associated with deformities of femur, knee, tibia, ankle, and foot. The femur is short and has lateral condylar hypoplasia, causing patellar

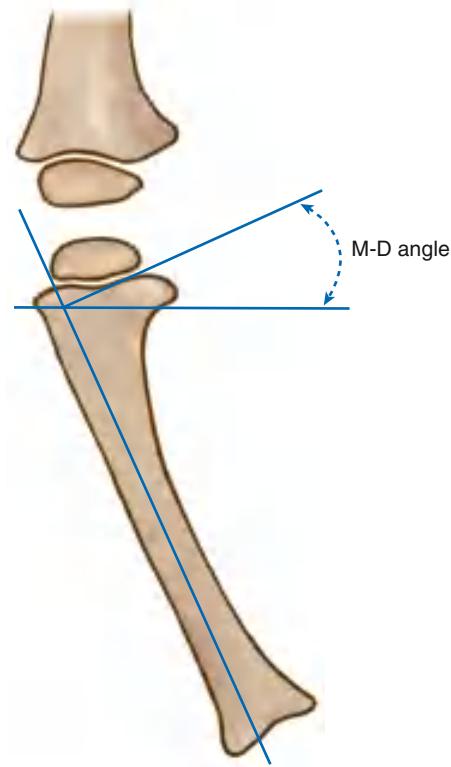


Fig. 716.11 Metaphyseal-diaphyseal (M-D) angle. Draw a line on the radiograph through the proximal tibial physis. Draw another line along the lateral tibial cortex. Last, draw a line perpendicular to the shaft line as demonstrated in the diagram. (From Morrissey RT, Weinstein SL, eds. Lovell and Winter’s Pediatric Orthopaedics, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 1990.)

instability and genu valgum deformity. The tibia has anteromedial bowing with reduced growth potential. The keys for management are addressing the ankle stability and foot deformities. The ankle resembles a ball-and-socket joint with lateral instability. The foot deformities are characterized by the absence of lateral digits, equinocavovarus foot, and tarsal coalition.

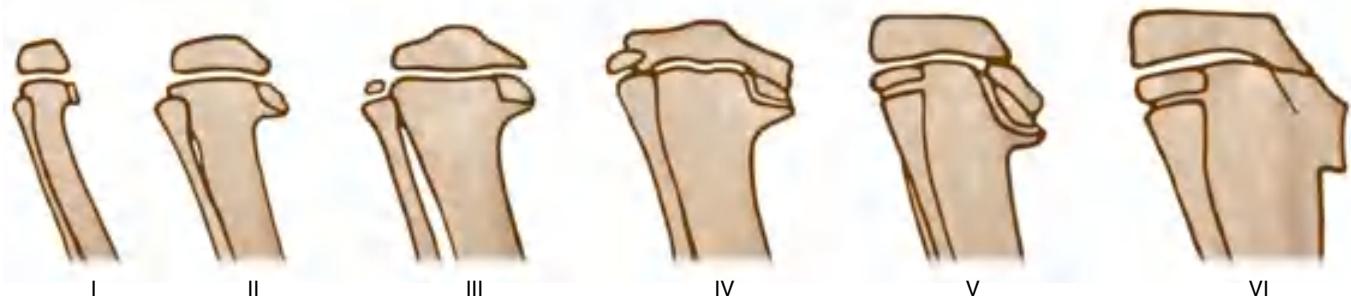


Fig. 716.12 Depiction of the stages of infantile Blount disease. (From Langeskiöld A. *Tibia vara [osteochondrosis deformans tibiae]: a survey of 23 cases*. Acta Chir Scand. 1952;103:1.)

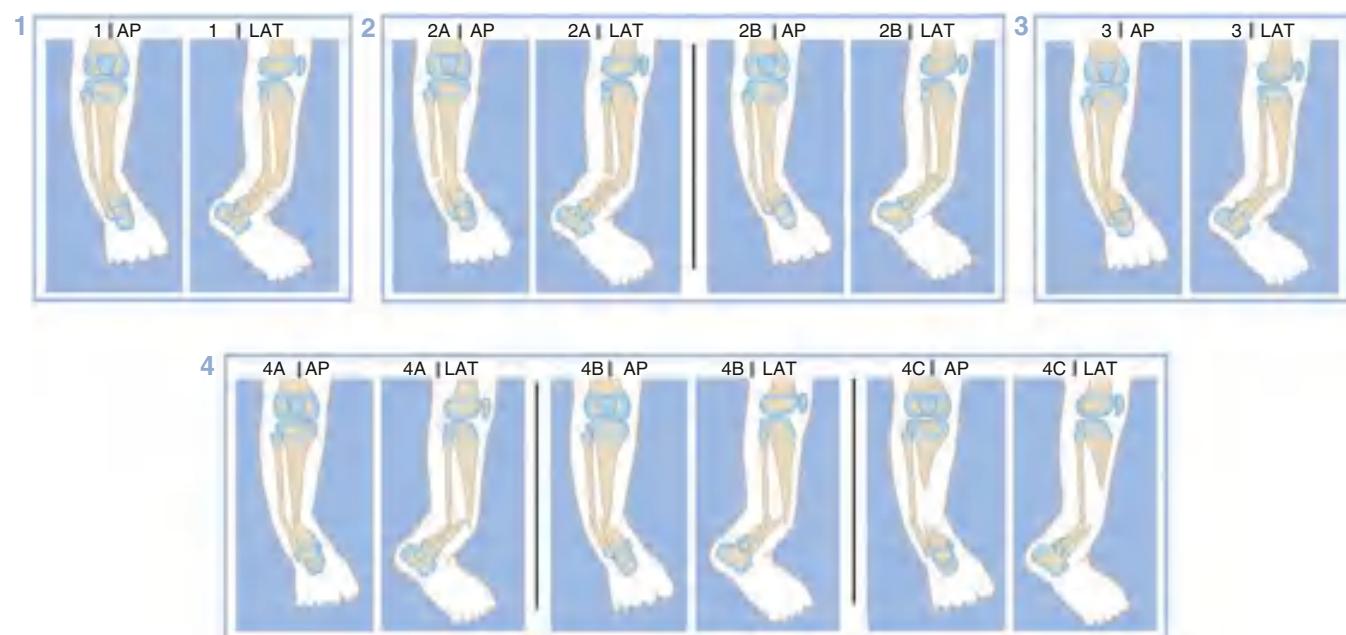


Fig. 716.13 Paley classification of congenital pseudarthrosis of the tibia. Paley: type 1, no fractures; type 2, no fracture tibia, fracture fibula with fibula (2A) at station (2B) proximal migration; type 3, fracture tibia, no fracture fibula; type 4, fracture tibia and fibula with fibula (4A) at station (4B) proximal migration (4C) bone defect tibia with proximal migration fibula AP, Anteroposterior; LAT, lateral. (Reproduced with permission by the Paley Foundation.) (From Paley D. *Congenital pseudarthrosis of the tibia: biological and biomechanical considerations to achieve union and prevent refracture*. J Child Orthop. 2019;13:120–133.)

Various surgical options have been described, and the treatment is tailored to the patient's needs and parents' acceptance. A severely deformed foot may be best managed with Syme or Boyd amputation and prosthesis as early as 1 year of age. In the salvageable foot, leg length discrepancy can be treated with contralateral leg epiphysiodesis or ipsilateral limb lengthening.

ANTEROLATERAL TIBIAL BOWING

Anterolateral tibial bowing is associated with **congenital pseudarthrosis of the tibia** (CPT). Previous estimates suggest that 50–60% of patients with CPT have **neurofibromatosis**; however, this prevalence may be underestimated as the diagnostic criteria for neurofibromatosis often become evident after CPT has been diagnosed. Overall, less than 10% of patients with neurofibromatosis have this lesion. The pseudarthrosis or site of nonunion is typically situated at the middle third and distal third of the tibia. The Boyd's classification identifies six types of CPT with increasing severity depending on the presence of cystic and dysplastic changes. The Paley classification is another frequently employed system (Fig. 716.13). The treatment for this condition has been very frustrating with poor results. Bracing has been recommended to prevent fracture early in the course but does not usually obviate need for later surgical intervention. Numerous treatment protocols and surgical procedures have been described to achieve union, such as single- and dual-onlay grafting with rigid internal fixation, intramedullary nailing with or without bone grafting, and circular frame fixation. With the growing use of microsurgery in orthopedics, vascularized

fibular autograft also has been used with varying results. Due to the rate of complications occurring during reconstructive treatment, a below-knee amputation with early rehabilitation is also an accepted treatment strategy for some of these patients.

TIBIAL LONGITUDINAL DEFICIENCY

Tibial longitudinal deficiency, or tibial hemimelia, follows an autosomal dominant inheritance pattern. Multiple classification systems have been described, all of which largely categorize patients based on which portion(s) of the tibia is deficient. The other associated anomalies are foot deformities, hip dysplasia, and symphalangism of the hand. Traditionally, treatment has been guided by the Jones classification, which describes presence of a proximal tibial anlage and a functional quadriceps mechanism. In type Ia deformity, the proximal tibial anlage is absent, and knee disarticulation with prosthesis is recommended. In types Ib and II, the tibial anlage is present, and the management consists of an early Syme amputation, followed later by synostosis of the fibula with the tibia, and a below-knee prosthesis. Type III is rare, and the principal management is with Syme amputation and a prosthesis. Type IV deformity is associated with ankle diastasis, which requires stabilization of the ankle and correction of leg length discrepancy at a later stage. Due to the varied pathology of this condition and its rarity, treatment options and recommendations continue to evolve.

Chapter 717

Leg-Length Discrepancy

Christine M. Goodbody and
Richard S. Davidson

A discrepancy in leg lengths may result from a variety of congenital or acquired conditions (Table 717.1). Although up to 25% of adults may have a difference of more than 1 cm, only a small percentage have more than a 2 cm difference, for which the main consequence is gait asymmetry. An increase in vertical pelvic motion is observed, and more energy must be expended during ambulation. Although a small compensatory lumbar curvature may develop, a small leg-length discrepancy (<2 cm) is unlikely to result in back pain, structural scoliosis, or degenerative arthritis. There is some evidence to suggest that larger, long-standing discrepancies may be associated with hip or knee arthritis, structural scoliosis, and spine degenerative changes. The goal of treatment is to have a discrepancy of <2–2.5 cm at skeletal maturity, and several treatment methods are available to achieve this objective. Knowledge of the underlying etiology, coupled with regular follow-up to assess limb growth and skeletal maturity, allows the treating physician to project the discrepancy at skeletal maturity and to plan treatment. A subset of patients will have coexisting abnormalities in the viscera or musculoskeletal system that must also be identified and treated.

DIAGNOSIS AND CLINICAL FINDINGS

Gait asymmetry is the most frequent complaint. The long leg is often kept flexed at the knee and hip in stance to level the pelvis. The diagnosis is made on physical examination, and specialized radiographs help to quantify the existing discrepancy and predict what the discrepancy will be at maturity. The discrepancy may be caused by hypoplasia, hyperplasia, or angular deformity (structural discrepancy), by soft-tissue contracture at the hips, knees, or ankles (apparent or functional shortening), or by a combination of these conditions. Other contributing factors include joint subluxation or dislocation (hip), a decrease in the height of the foot (congenital or neuromuscular), or structural disorders of the pelvis. A careful physical examination is required to identify all factors contributing to the discrepancy. Muscle contracture about the hip will also create the appearance of leg-length inequality. For example, to bear weight on an abducted hip, the patient must hike up the contralateral hip and pelvis, making the contralateral leg appear short.

There are several clinical methods for measuring the extent of the limb-length discrepancy. The preferred method is to perform a standing examination in which blocks of various sizes are placed under the short leg until the pelvis is leveled (Fig. 717.1). An alternate method is to measure the length of each leg with the patient supine; the examiner first extends the patient's legs and examines the soles of the feet for asymmetry before flexing the patient's hip to 90 degrees to evaluate for discrepant knee height (Galeazzi sign). Using a tape measure is very inaccurate because of several variables, including the line of measurement used, muscle atrophy, and moving patients. The range of motion at the hip, knee, and ankle must also be assessed to identify any causes of apparent discrepancy. A 10-degree fixed abduction (or adduction) contracture of the hip may create an apparent leg-length discrepancy of 2–3 cm. Similarly, a flexion contracture of the hip and/or knee will create apparent shortening of the extremity, whereas an equinus contracture at the ankle will create apparent lengthening of the extremity. A rigid lumbar scoliosis (suprapelvic contracture) will create pelvic obliquity and an associated apparent limb length inequality. Once a discrepancy is quantified in a child, it must be followed at regular intervals until maturity. Assessments at 6- to 12-month intervals are most common depending on the rate of change.

Leg-length discrepancy may be associated with various **genetic overgrowth syndromes** (see Table 717.1). If there are features other than leg-length discrepancy, specific diagnostic tests for Beckwith-Wiedemann syndrome and *PIK3CA* pathogenic variants must be included in the patient's evaluation. In these disorders, the leg overgrowth tends to increase over time.

RADIOGRAPHIC EVALUATION

Radiologic evaluation complements the clinical examination; both are typically used when making treatment decisions. For an accurate assessment, it is important that the child not move and keep their legs extended; a lift may help. Five different techniques are available. The **teleoroentgenogram** is a single radiographic exposure of both lower extremities (standing) and requires a long cassette. A ruler is placed on the film, and direct measurements are made, factoring in a 6% magnification error, which is usually accounted for using a radiographic marker of known diameter to calibrate the image. One advantage is that angular deformities may be assessed. Its primary indication is for young children. Unfortunately, because only one exposure is used for the leg and because the ankle is less dense than the hip, it may be difficult to "see" the whole leg. In addition, because the x-ray source is at the knee projecting up to the hip and down to the ankle, this method projects the hip and ankle along the ruler, making the leg appear longer than it really is, particularly in obese patients. The **orthoroentgenogram** consists of three separate exposures of the hips, knees, and ankles on a long cassette. The patient is supine, and a ruler is placed on the cassette for measurement of bone length. However, the patient must lie still for the three exposures, which is often difficult to achieve in younger children. Because the x-ray beam is pointed at the hip, knee, and ankle in each of the three exposures, the length measurement is accurate and each of the three joints can be exposed properly. The x-rays expose from the top of the pelvis to the mid femur, from the mid femur to the mid tibia, and from the mid tibia to below the foot for each of the three exposures, respectively, permitting angular deformity assessment in the frontal plane only. The **scanogram** also consists of separate exposures of the hips, knees, and ankles on a cassette with a radiographic ruler; a chest-sized film cassette is used (Fig. 717.2). There is no magnification error; patients must remain still for the three exposures, and angular deformities cannot be assessed. Although CT is an accurate technique, the assessment is time-consuming, and the patient receives a larger dose of radiation. In addition, a radiologist must normalize the axis of the leg to the screen to accurately measure the limbs. An advantage of CT is that limb and segment lengths can be measured even if there are soft tissue contractures or deformity in the sagittal plane. Another popular technique is called **EOS**. EOS is a proprietary low-dose x-ray scanner that can simultaneously take orthogonal full-body images in a standing position and is therefore able to reconstruct three-dimensional (3D) images of the bony anatomy in question (Fig. 717.3). The advantages of EOS are that it has a much lower radiation dose than standard x-rays, it can capture frontal and sagittal planes quickly and simultaneously, and there is no magnification error. The disadvantages are that it requires a trained radiology technician to correctly align the limbs for computer measurement, and not all centers have access to the technology at this time. Regardless of the technique, it is critical that the patellae be pointed forward, that measurements be made in the plane of the limb, that the legs be extended, and that the same method be used in sequential measurements to be compared.

In the presence of flexion or extension deformities where 3D imaging is not employed, each bone should be x-rayed individually with a ruler where the x-ray beam is perpendicular to the bone and the ruler parallel to the bone.

In addition to quantifying the discrepancy, it is essential to determine skeletal age (bone age) to assess how much growth a patient has left and to assist in estimating the size of discrepancy at maturity. An anteroposterior radiograph of the hand and wrist is usually obtained at each visit and compared with the standards in the Greulich and Pyle Atlas to estimate skeletal age. Although more accurate techniques are available, most are time-consuming and impractical for routine clinical

Table 717.1 Causes of Lower Extremity Length Discrepancy

SHORTENING	LENGTHENING	SHORTENING	LENGTHENING
CONGENITAL Hemiatrophy* Skeletal dysplasias Short femur Proximal focal femoral deficiency* Fibular, tibial hemimelia Developmental dysplasia of the hip*	CONGENITAL Hemihypertrophy* Local vascular malformation	NEUROMUSCULAR DISEASE Polioymelitis Cerebral palsy* Myelomeningocele Peripheral neuropathy Focal cerebral lesions (hemiplegia)	
TUMOR Developmental Neurofibromatosis Multiple exostosis Enchondromatosis (Ollier disease) Osteochondromatosis Fibrous dysplasia (Albright syndrome) Punctate epiphyseal dysplasia Dysplasia epiphysealis hemimelica (Trevor disease) Radiation therapy before skeletal maturity (physeal arrest)* Resection of benign or malignant neoplasm	TUMOR Developmental Neurofibromatosis Soft tissue hemangioma Arteriovenous malformation Hemihypertrophy with Wilms tumor Aneurysm	OTHER Legg-Calvé-Perthes disease* Slipped capital femoral epiphysis	LATERALIZED OVERGROWTH (HEMIHYPERPLASIA SYNDROMES) Beckwith-Wiedemann syndrome <i>PIK3CA</i> related overgrowth spectrum (PROS) Klippel-Trenaunay syndrome CLOVES (congenital lipomatous overgrowth, vascular malformations, epidermal nevi, scoliosis/skeletal, spinal) Isolated lymphatic malformation Fibroadipose vascular anomaly Megalencephaly—capillary malformation Hemimegalencephaly /dysplastic megalencephaly/focal cortical dysplasia Muscular hemihyperplasia Fibroadipose hyperplasia or overgrowth CLAPO syndrome (capillary malformation of lower lip, lymphatic malformation of face and neck, asymmetry of face and limbs and partial or generalized overgrowth)
INFECTION Osteomyelitis* Septic arthritis Tuberculosis	INFECTION Inflammation Metaphyseal osteomyelitis Rheumatoid arthritis Hemarthrosis (hemophilia)		
TRAUMA Physeal injury* Failed joint replacement Osteotomy, atrophic nonunion Overlapping, malposition of fracture fragments* Burns	TRAUMA Metaphyseal, diaphyseal fracture Diaphyseal operations (bone grafts, osteosynthesis, periosteal stripping)		

*Common.

Modified from Moseley C. Leg-length discrepancy. *Pediatr Clin North Am.* 1986;33(6):1385.

application. The range of variability using the atlas is approximately 9 months, so the method is most accurate when multiple data points have been collected. Apps to calculate the discrepancy at maturity and timing of treatment are available.

TREATMENT

Options for treatment include observation, a shoe lift or custom orthosis, a limb-shortening procedure (acute shortening and internal fixation versus gradual shortening by growth arrest or guided growth), a limb-lengthening procedure (with internal or external fixation), or a combination of these. Deformity correction is often accomplished simultaneously. In the congenital deficiencies (femur, tibia, fibula) in which the predicted limb-length inequality will require more than three lengthening operations (more than 20 cm), an early foot amputation may be the best option to achieve an optimal functional outcome. In addition to the magnitude of discrepancy predicted at skeletal maturity, both the anticipated adult height of the patient (estimated from family members) and the desires of the patient and the patient's family are important considerations.

Discrepancies of up to 2.5 cm may be treated by observation or a shoe lift. With regard to a shoe lift, up to 1 cm may be placed within the shoe, and up to 5 cm may be placed on the outside of the shoe. Complete correction of inequality is not required, and the height of the lift should be adjusted based on the patient's gait and comfort. An orthotic may be used as a temporizing measure before definitive treatment. For extended discrepancies, "foot in foot" extension prostheses are a

reasonable alternative until limb lengthening can be accomplished or for patients who cannot or do not wish to undergo surgical correction.

For patients with a predicted ultimate discrepancy between 2 and 5 cm, an **epiphysiodesis** is offered in skeletally immature patients, and an acute shortening may be performed in a skeletally mature patient. Epiphysiodesis refers to a temporary or permanent cessation of growth at one or more physes. A permanent growth arrest is most commonly performed when sufficient data are available with which to accurately predict when to perform the procedure. Approximately 65% of the growth of the lower extremity comes from the distal femur (37%, 9 mm/year) and proximal tibia (28%, 6 mm/year). Males typically grow until 16 years of age, whereas females grow until 14 years of age. As such, performing an epiphysiodesis of both the distal femur and the proximal tibia in a patient with 3 years of growth remaining should achieve approximately 4.5 cm of correction. Techniques used to determine the timing of epiphysiodesis are the Menelaus method ("rule of thumb"), the Green and Anderson method, the Moseley straight-line graph, and the multiplier method (Figs. 717.4-717.6). Apps to make calculations are available. The most common surgical technique for permanent growth arrest is the percutaneous epiphysiodesis, in which the physis is ablated with a drill and curetted under image intensification. This is an outpatient procedure with few complications. Insertion of plates and screws or just screws across the physis is an alternative but usually requires a second operation to remove the hardware. For patients for whom sufficient data are unavailable or those for whom the underlying diagnosis is associated with an unpredictable pattern



Fig. 717.1 Clinical assessment of limb length inequality with the aid of graduated blocks. (A) True leg length inequality (or fixed functional discrepancy) results in asymmetric iliac crest or posterior iliac spine heights with the patient standing erect. The examiner must be sure that the patient is standing evenly on the legs, with the knees straight and the feet flat on the floor. (B) A reasonably accurate estimation of leg length inequality can be made by having the patient stand erect on sufficient graduated blocks under the shorter limb to level the pelvis. (From Podeszwa D. Limb length discrepancy. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig 20.3.)



Fig. 717.2 Scanogram to demonstrate exact leg-length discrepancy.

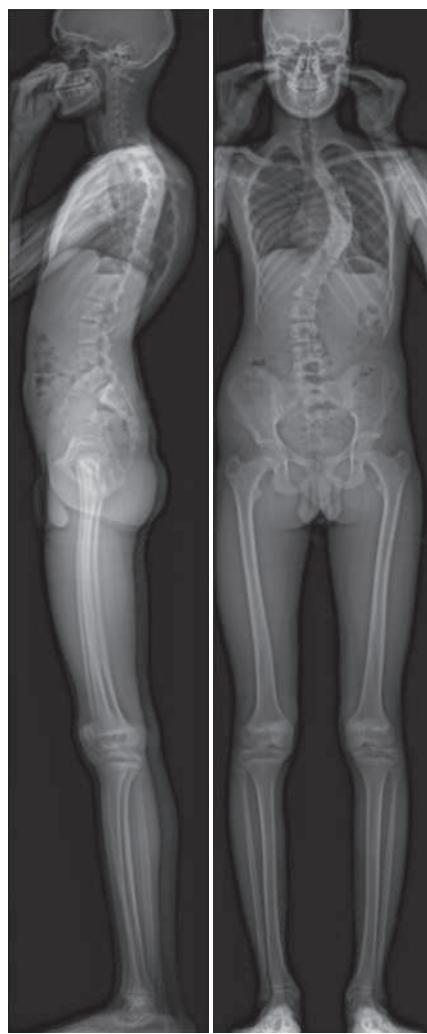
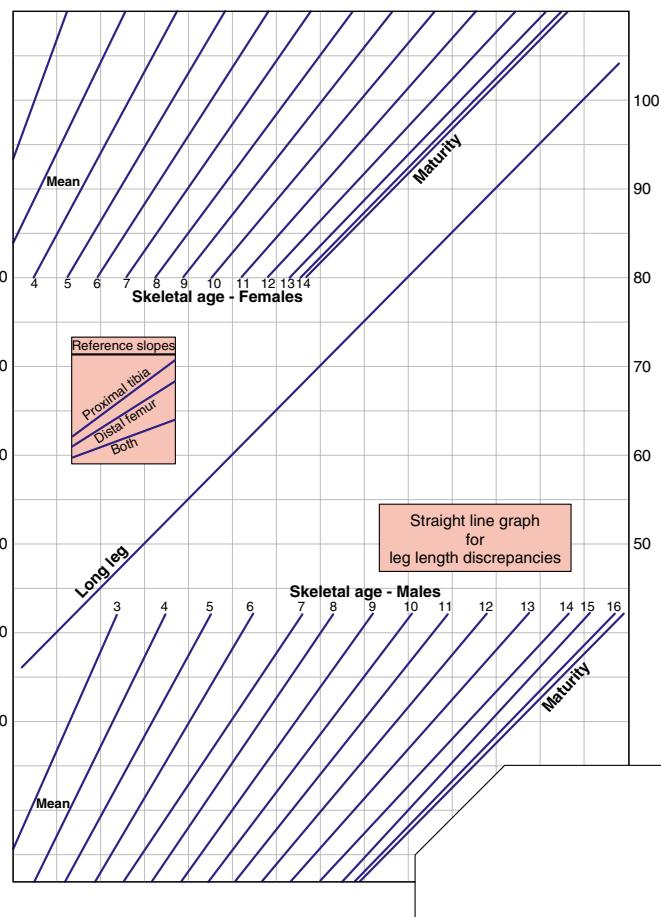
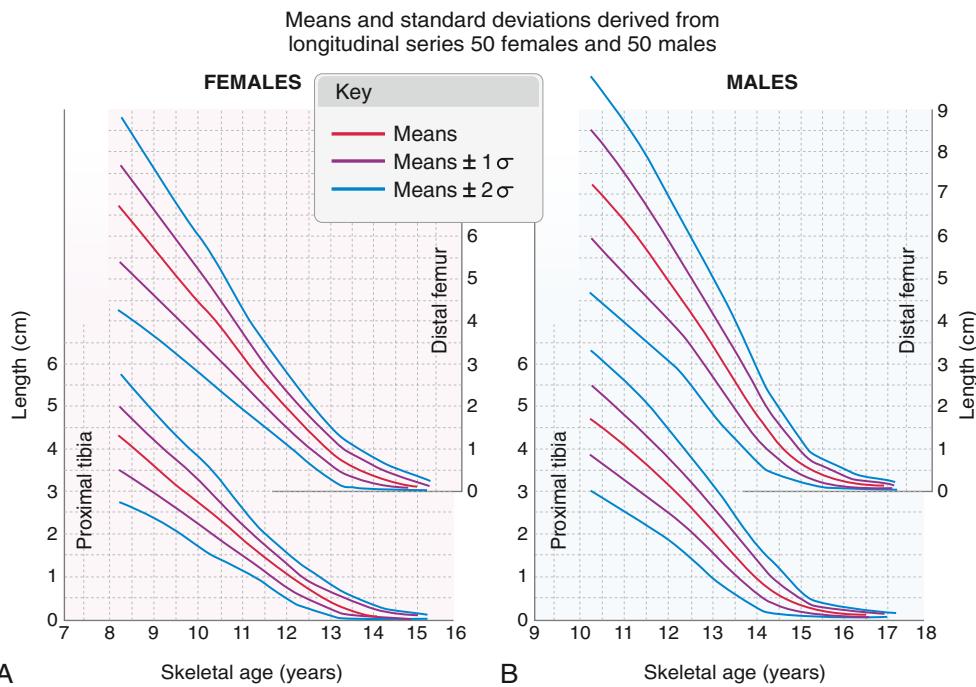


Fig. 717.3 2D Biplanar Whole Body EOS Imaging. (From Garg B, Mehta N, Bansal T, Malhotra R. EOS Imaging: concept and current applications in spinal disorders. *J Clin Orthop Trauma*. 2020;11:786–793. Fig. 2.)

of growth, then a reversible technique, such as staples, plates, and/or screws, may be considered. Once equalization has been achieved, the hardware can be removed, allowing growth to resume. When the patient is skeletally mature or if it is deemed appropriate to wait until maturity before treatment, depending on the magnitude of deformity and patient/family preference, acute shortening may be the best option. Acute shortening is typically performed at the femur (several techniques have been described), given the increased risk of complications associated with shortening of the tibia and fibula including compartment syndrome and neurovascular problems.

For discrepancies >5 cm after maturity, or for smaller ones depending on patient/family preference, lengthening of the short limb is the procedure of choice. An exception would be a discrepancy secondary to overgrowth of one limb, in which acute or gradual shortening of the abnormal limb would be preferred so as to preserve body proportions. Patients with anticipated discrepancies $>8-10$ cm often require one or more limb-lengthening procedures (several years apart), with or without an epiphysiodesis to mitigate the size of the ultimate discrepancy and need for more than one lengthening. The most common technique used for limb lengthening involves placement of an intramedullary magnetic lengthening nail or an external fixator, either a ring fixator such as the Ilizarov device or a monolateral device (Fig. 717.7). The bone is cut at the metaphyseal-diaphyseal junction, and lengthening is achieved gradually through distraction at the corticotomy. The usual rate



Multiplier for Males and Females (Paley et al, 1999)			
Males		Females	
Age	Multiplier	Age	Multiplier
0	5.08	0	4.63
0.4	4.01	0.3	4.01
1	3.24	1	2.97
1.3	2.99	2	2.39
2	2.59	3	2.05
3	2.23	3.3	2.00
4	2.00	4	1.83
5	1.83	5	1.66
6	1.68	6	1.53
7	1.57	7	1.43
8	1.47	8	1.33
9	1.38	9	1.26
10	1.31	10	1.19
11	1.24	11	1.13
12	1.18	12	1.07
13	1.12	13	1.03
14	1.07	14	1.00
15	1.03	15	1.00
16	1.01	16	1.00
17	1.00		
18	1.00		

LLD Prediction Formulas

Prenatal LLD (congenital)
 $\Delta_m = \Delta \times M$

Postnatal LLD (developmental)
 $\Delta_m = \Delta + I \times G$

Inhibition $\approx I = 1 - \frac{S - S^*}{L - L^*}$

Growth remaining $= G = L(M - 1)$

$\Delta_m = \text{LLD at maturity}$

$\Delta = \text{Current LLD}$

$L \& S = \text{Current length of long and short leg}$

$L^* \& S^* = \text{Length of long and short leg at any other date since LLD began}$

Fig. 717.6 Paley multiplier. This is a simple method of determining the leg-length discrepancy (LLD) at maturation. This is applicable for shortening conditions in which growth retardation is consistent. (From Paley D, Bhave A, Herzenberg JE, et al. Multiplier methods for predicting limb-length discrepancy. J Bone Joint Surg Am. 2000;82:1432–1446.)

of lengthening is 1 mm/day in the femur and 0.75 mm/day in the tibia, and it takes approximately 1 month of wearing the fixator for each centimeter of length gained with a minimum of 3 months in the fixator. Additional time in the fixation device may be required for pathologic bone or for metabolic diseases affecting bone formation. A maximum of 15–25% of the original length of the bone may be gained at each session and is limited by tolerance of the soft tissues and nearby neurovascular structures. An advantage of



Fig. 717.7 Ilizarov device demonstrating bone lengthening by distraction osteogenesis.

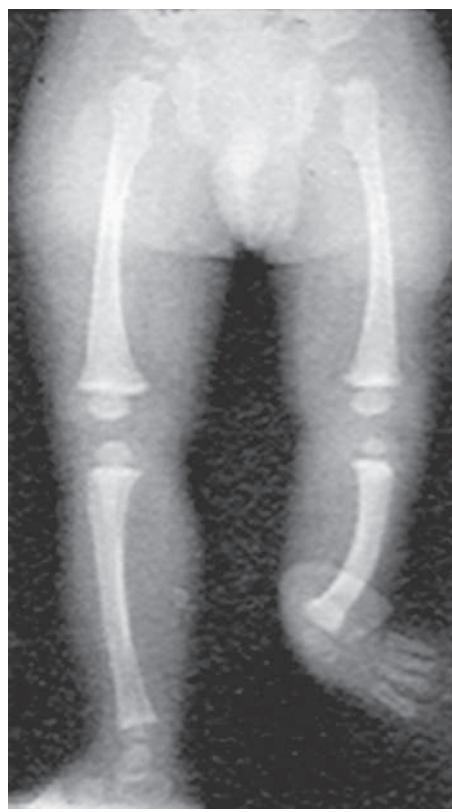


Fig. 717.9 Anteroposterior radiograph of fibular hemimelia with leg-length discrepancy.



Fig. 717.8 Extension prosthesis leg-length discrepancy (A) and compensated with extension prosthesis (B).

the circular fixator or multiaxial external fixators is the ability to correct coexisting angular deformities at the same time. Technologic advances have allowed the development of totally implantable intramedullary lengthening rods driven by external magnets. Internal lengthening has become the procedure of choice for patients whose age and anatomy are appropriate for the procedure, especially in the femur where external fixation is more poorly tolerated. These devices may provide improvements in patient satisfaction and reduced complications, including a lower rate of contracture and absence of pin site infection. New technologies for internal lengthening in skeletally immature patients whose physes cannot safely be violated by a rigid nail are actively under study. Complications of limb lengthening include pin tract infection (most common), wound infection, hypertension, joint subluxation, muscle contracture, stretch-induced nerve palsy, premature consolidation, delayed union, implant-related problems, and fractures after implant removal.

Early amputation and prosthetic fitting may provide the best long-term function in patients with projected discrepancies in excess of 18–20 cm, especially when there are coexisting deformities or deficiencies of the ipsilateral foot (Figs. 717.8 and 717.9). The alternative would be multiple reconstructive procedures throughout childhood and adolescence. The cultural and personal values of the child and family, as well as the impact of multiple procedures on the child's psychosocial development, must also be kept in mind when formulating the treatment plan in these complex cases.

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Chapter 718

The Knee

Anne M. Coyle and J. Todd R. Lawrence

NORMAL DEVELOPMENT OF THE KNEE

The knee is a synovial joint and forms between the third and fourth months of fetal development. Secondary ossification centers form between the sixth and ninth fetal months at the distal femur and between the eighth fetal month and the first postnatal month at the proximal tibia. The patellar ossification center does not appear until 2-4 years of age in females and 3-5 years of age in males.

ANATOMY AND RANGE OF MOTION

The knee is the largest joint in the body and acts primarily as a modified hinge. The distal femur is cam shaped, with the medial and lateral femoral condyles having slightly different shapes. The shape of the articular surfaces allows the femur to glide posteriorly on the tibial plateau during knee flexion and also permits approximately 8-12 degrees of rotation through the flexion and extension arc. The normal range of motion of the knee is from neutral (or fully straight) to 140 degrees of flexion. Increased ligament laxity, including hyperextension of up to 10-15 degrees, can be normal in many children. Most activities can be performed in the flexion arc of 0-70 degrees.

The knee consists of three articulations: *patellofemoral*, *tibiofemoral*, and *tibiofibular*. The anterior and posterior cruciate ligaments as well as medial and lateral collateral ligaments stabilize the knee during movement. The medial and lateral menisci provide support under compressive forces, helping to redistribute the forces from the more rounded distal femur to the flatter proximal tibia. The medial patellofemoral ligament is the primary static soft tissue restraint against lateral patellar displacement. There are also several bursae located about the knee to cushion and reduce friction on tendons acting across the knee joint.

718.1 Discoid Lateral Meniscus

Anne M. Coyle and J. Todd R. Lawrence

Discoid lateral meniscus (DLM) is a congenital anatomic variation of the lateral meniscus that may be asymptomatic or cause the classic **snapping knee syndrome**. Many cases are asymptomatic for years, making the true incidence difficult to determine. DLM is estimated to occur in 3-5% of children and adolescents and is bilateral in about 20% of cases.

Anatomically, the normal meniscus (Fig. 718.1A) is attached around its periphery and at the tips of the "C" anteriorly and posteriorly onto the tibia. During knee motion, the meniscus translates anteriorly and posteriorly to match the slight rollback of the lateral femoral condyle on the tibia with knee flexion. However, with DLM, the meniscal tissue trapped between the articular surfaces is pushed anteriorly as the knee flexes. These abnormal forces, over time, result in tears in the meniscal tissue, the peripheral attachments, or both. Tearing or stretching of this tissue allows for excessive meniscal displacement during knee range of motion. Usually a pop is heard or sensed when flexing at about 90-120 degrees of knee flexion as the meniscus is extruded anteriorly and a loud click or clunk is heard when extending the knee in the last 30 degrees of extension as the meniscus reduces back between the joint surfaces.

The **Watanabe classification system** defines three types of DLM based on arthroscopic appearance. A type I, or **complete discoid lateral meniscus**, is characterized by a thickened lateral meniscus with complete coverage of the tibial surface (see Fig. 718.1B). Because meniscus tissue is always between the joint surfaces with this type of

discoid meniscus, it is the type most commonly associated with the knee snapping characteristic of DLM. A type II, or **incomplete discoid lateral meniscus**, is of variable size and covers a lower percentage of the tibial surface (see Fig. 718.1C) compared to the complete type. Although the meniscus can become stretched or torn over time, both the complete and the incomplete types are thought to develop with normal peripheral attachments. A type III, or **Wrisberg variant lateral meniscus**, has no peripheral attachments posteriorly. Instead, it is stabilized posteriorly only by a prominent meniscofemoral ligament, or ligament of Wrisberg, that secures the posterior horn of the lateral meniscus to the lateral surface of the medial femoral condyle (see Fig. 718.1D). As a result, the Wrisberg ligament type of DLM is extremely mobile. Although its shape is not necessarily discoid, the hypermobility of the posterior portion of the meniscus allows it to be extruded anteriorly with flexion and for it to pop back into place with extension, allowing it to present with the same snapping knee pain characteristic of the other DLM variants.

CLINICAL MANIFESTATIONS AND DIAGNOSIS

All types of DLM can be asymptomatic, especially if they have stable peripheral attachments and no tears (see Fig. 718.1). Patients with *symptomatic* DLM usually present with complaints of lateral knee pain and examination findings consistent with a meniscal tear or meniscal instability because of absent peripheral attachments, allowing for anterior extrusion during flexion and reduction with extension thus producing the classic snapping knee. Although patients can present as early as 2 years of age, presentation after 6 years of age is typical, with the highest incidence of presentation during the teenage years.

Younger children usually present with no history of trauma or acute inciting event but rather with a complaint of popping in the knee with occasional swelling as a result of peripheral tears or instability of the meniscus. Older children and adolescents often can recall an inciting event and will sometimes report a history of the mechanical popping. However, they more often note lateral joint line pain and knee swelling. Weight gain during the adolescent growth spurt places increased static and dynamic loads on the tissue, especially during high-level sports. In these patients, degeneration in the central portion of the DLM with direct weight-bearing makes the meniscus highly susceptible to injury and tears, producing the lateral pain and swelling in the knee. Often, the classic popping is not appreciated in these patients.

Physical examination often shows a mild effusion and tenderness over the lateral joint line. For patients with an unstable meniscus, when the knee is fully flexed, a pop with a slight protuberance along the lateral joint line anteriorly can sometimes be appreciated as the meniscus is extruded anteriorly. When the knee is brought back into extension at approximately 20-30 degrees short of full extension, the meniscus can be felt to snap back in place and the protuberance at the lateral joint line disappears.

A high level of suspicion is necessary based on history and clinical examination findings because many patients will present with a complaint that their knee is "dislocating." Radiographs including standard anteroposterior (AP), lateral, merchant (patellar), and 45 degrees flexed posteroanterior (PA) (tunnel) views should be obtained if this diagnosis is considered. Radiographs may appear normal or show findings that include widening of the lateral aspect of the knee joint, flattening of the lateral femoral condyle (resulting in a squared-off appearance), lateral tibial spine hypoplasia, and cupping of the lateral aspect of the tibial plateau. Because these findings are very nonspecific, with any history or physical examination findings suggestive of DLM, evaluation using MRI will provide a definitive diagnosis. Diagnosis on MRI is made if the ratio of the minimal meniscal width to the maximal tibial width in the coronal plane is >20% and/or if continuity between the anterior and posterior horns of the meniscus is present on three or more consecutive slices in the sagittal plane.

TREATMENT

Patients with asymptomatic or incidentally found DLM without evidence of a tear or meniscal instability do not require treatment. They should be educated on symptoms to anticipate, but activity restriction

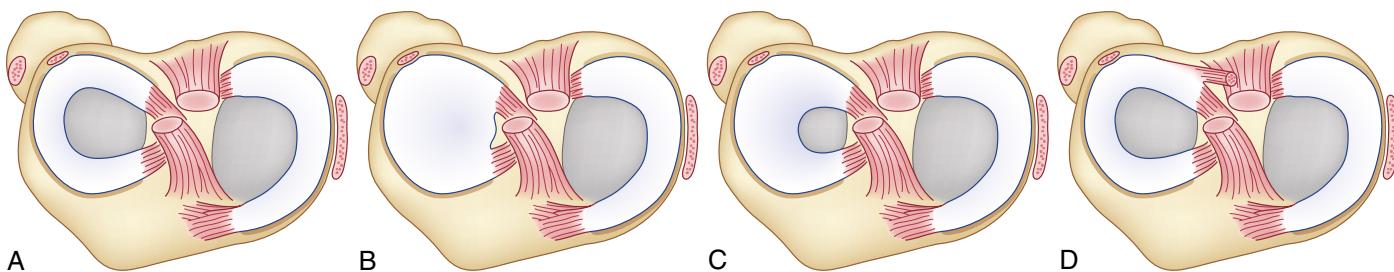


Fig. 718.1 The anatomy of the normal meniscus and discoid variants. A, The lateral meniscus normally has a C shape with circumferential and root attachments. B, A type I, or complete, discoid lateral meniscus covers the entire tibial plateau and has normal attachments. C, A type II, or incomplete, discoid lateral meniscus partially covers the tibial plateau and also has normal attachments. D, A type III, or Wrisberg ligament type, appears similar in shape to a normal lateral meniscus but lacks sufficient attachments posteriorly resulting in a hypermobile meniscus. The ligament of Wrisberg secures the posterior horn of the meniscus to the lateral aspect of the medial femoral condyle.

is not usually necessary. If knee pain or mechanical symptoms are persistent and limit activity or if a meniscal tear develops, surgical intervention should be considered. Partial meniscectomy, referred to as **saucerization**, is often performed to reshape the meniscus arthroscopically with the goal of obtaining an anatomically normal-appearing meniscus (Fig. 718.2). Tears remaining in what would be the normal rim of meniscal tissue are either repaired or excised. Meniscal instability is also addressed with repairs as appropriate. Because tears that extend from the center of the meniscal tissue all the way to the peripheral rim are difficult to repair and removing this much meniscal tissue leaves the joint surfaces unprotected, leading to early osteoarthritis, addressing DLM tears as soon as they develop and before they extend to the periphery is preferred. Approximately 9–17% of patients require repeat operation, which is almost always due to repeated tear of the meniscus. Patients with symptomatic DLM are 4.5 times more likely to eventually require surgical treatment on their other knee.

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718.2 Popliteal Cysts (Baker Cysts)

Anne M. Coyle and J. Todd R. Lawrence

Popliteal cysts or Baker cysts are simple cystic masses filled with gelatinous material that develops in the popliteal fossa, the shallow depression located at the posterior part of the knee. They are considered rare in children. They most commonly occur in the region of the medial head of the gastrocnemius and semimembranosus muscles as an isolated fluid-filled bursa or via herniation through the posterior joint capsule of the knee into this same location. Histologically, the cysts are classified as fibrous, synovial, inflammatory, or transitional. Typically, popliteal cysts resolve spontaneously, although the process may take several years.

CLINICAL MANIFESTATIONS AND DIAGNOSIS

Patients commonly present with a unilateral mass behind the knee that may be fairly large when first noted. Typically, there is no associated history of trauma or knee injury. Physical examination reveals a firm but compressible mass in the popliteal fossa, often medially located and distal to the popliteal crease. The mass is usually most prominent when the knee is extended. Transillumination of the cyst on physical examination is a simple diagnostic test. Knee radiographs are normal but should be obtained to rule out other lesions, such as osteochondromas, osteochondritis dissecans, and malignancies. Ultrasoundography, MRI, or aspiration may confirm the diagnosis. Ultrasound can be used to confirm a simple cystic lesion in the expected anatomic location and is often the only diagnostic test necessary with these reassuring findings. However, if a solid mass, vascular lesion, or complex cystic lesion is identified on ultrasound, an MRI may be used to further evaluate the mass. Additionally, in the presence of a knee effusion, an MRI should be considered to evaluate for knee intraarticular pathology that may be

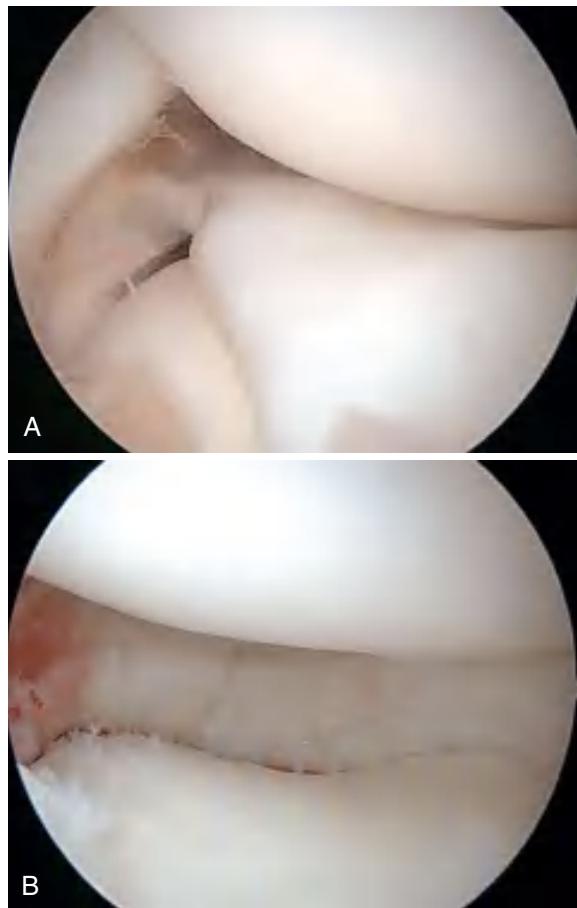


Fig. 718.2 Surgical treatment of discoid lateral meniscus. Arthroscopic images of a complete discoid lateral meniscus before (A) and after (B) partial meniscectomy.

causing the swelling. These children should also be assessed for other pathology that may cause recurrent or intermittent knee effusions, including Lyme disease, juvenile idiopathic arthritis, or other autoimmune processes. The presence of a solid mass detected on ultrasound or MRI warrants additional diagnostic testing and referral for biopsy.

TREATMENT

In most cases, reassurance is all that is needed for popliteal cysts because they often resolve spontaneously. Rest and leg elevation can be suggested to promote drainage of the fluid accumulating within the cyst. In rare cases in which the cyst is persistently symptomatic, treatment options include aspiration to reduce the size of the cyst and/or corticosteroid injection to reduce inflammation. However, because

cysts often recur after treatment, the risk of these procedures is not usually worth the benefits. Surgical excision of a popliteal cyst is indicated only when symptoms are debilitating and have not resolved after an extended period of conservative treatment. If surgical excision is pursued, concurrent arthroscopic treatment of underlying joint pathology is typically recommended to significantly decrease recurrence rates.

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718.3 Juvenile Osteochondritis Dissecans

Anne M. Coyle and J. Todd R. Lawrence

Osteochondritis dissecans (OCD) is a localized pathologic process of the subchondral bone that secondarily affects the overlying articular cartilage and can progress to instability of the lesion with cartilage separation and fragmentation. Although OCD may occur in different joints, including the elbow and ankle, 75% of lesions are seen in the knee. Emerging evidence suggests that the cause of OCD is vascular insult to the developing knee that is unable to heal because of repetitive microtrauma. The disorder is being seen with rising frequency in children and adolescents, with a higher incidence in patients >12 years old, likely in large part because of the increased sports participation of young athletes. OCD is more common in active children, and about 60% of cases occur in participants of high-level athletics. The natural history of juvenile OCD is not the same as that seen in adults. In the knee, OCD most commonly affects the lateral aspect of the medial femoral condyle; however, the lateral femoral condyle and patella may also be affected. Failure of both the bone and the cartilage surface to heal completely is associated with an increased risk for developing premature osteoarthritis. Although the exact incidence of OCD is unknown, it is estimated to occur bilaterally in 14–20% of patients.

CLINICAL MANIFESTATIONS AND DIAGNOSIS

The most common presenting complaint is a vague or deep knee pain that is often activity related with no history of significant trauma to the knee. If the osteochondral fragment becomes unstable, the patient may also develop mechanical symptoms, such as catching or locking. Physical examination findings include effusion, tenderness to palpation over the femoral condyles, quadriceps atrophy, and diminished range of motion. It is important to conduct a thorough history and physical examination because several other conditions can present similarly in the pediatric population, including torn meniscus, patellofemoral pain syndrome, and hip pathologies such as Legg-Calvé-Perthes disease and slipped capital femoral epiphysis.

Imaging evaluation of OCD typically includes plain radiographs and MRI. Radiographs can establish the diagnosis and can be used to evaluate the treatment response. Because most OCD lesions are located more on the posterior aspect of the femoral condyle, a PA radiograph with a 45-degree flexed knee (tunnel view) is often required to evaluate for the presence of an OCD. Many of these patients also have some degree of patellar-related pain, necessitating merchant (patellar) view plain films. Thus standard radiographic evaluation of nontraumatic adolescent knee pain should routinely include AP, lateral, tunnel, and merchant radiographs of the knee. An early lesion may appear as a small radiolucency at the articular surface. A more advanced lesion may have a well-demarcated segment of subchondral bone with a lucent line demonstrating separation from the condyle. The clinical significance of irregularities in the ossification center of the developing epiphysis in children younger than 10 years is unclear.

MRI is useful for both diagnosing and characterizing OCD lesions. It can be used to determine the size and stability of the OCD, the integrity of the articular cartilage, and the presence of loose bodies. Fluid observed between the fragment and subchondral bone suggests an unstable lesion and a high risk for detachment. Any linear signal through the articular cartilage or displacement of the fragment indicates a potentially unstable lesion as well. Cysts surrounding the OCD can indicate instability if there are multiple or they are large in size.

However, when deciding treatment, it is important to consider both the clinical and radiographic findings as the ability of MRI to predict OCD stability in the pediatric population has been reported to be only 30–92% accurate. For an unstable-appearing OCD, based on either the patients' symptoms and signs or the imaging, arthroscopy is considered the gold standard to determine stability and should be performed to evaluate the status of the lesion.

TREATMENT

Treatment for juvenile OCD includes nonoperative and surgical management, with treatment decisions being based on many factors, including the growth status and skeletal maturity of the patient, the presence of symptoms, the size of the lesion, whether the lesion appears intact and stable, or if there is any suggestion of instability. The rate of juvenile OCD healing without surgical intervention is estimated to be 30–60%. Skeletal immaturity (i.e., younger age), smaller lesion size, and the absence of mechanical symptoms or pain have been associated with a higher likelihood of OCD healing with nonoperative treatment. Unstable OCD lesions will not usually heal with conservative treatment and thus almost always require surgical intervention.

Young patients with stable lesions, as evidenced by an intact articular surface on imaging (Fig. 718.3A), are deemed to have an acceptable probability of healing and are often initially managed conservatively with a period of restricted weight-bearing and immobilization, followed by a period of strict activity restriction and physical therapy for 3–6 months. OCD healing is followed with radiographs, usually at intervals of approximately 1.5–3 months, until lesion healing has been noted. If healing has not been radiographically confirmed in 3–6 months, surgical intervention is often considered. Because of the low rate of healing in skeletally mature patients, even intact lesions are not usually managed conservatively in this patient population, and surgery is recommended.

Although nonsurgical treatment may be successful in stable lesions, surgical treatment of these lesions is often more successful. Surgery also seems to induce healing at a faster rate than conservative treatment. Because surgical treatment has a very low complication rate and a time frame of recovery that closely parallels a course of conservative treatment, some patients may choose to pursue early surgical intervention instead of trying nonoperative treatment first. For stable and intact lesions, surgical management involves arthroscopic evaluation of the joint followed by either a transarticular or retroarticular drilling to stimulate bony healing by creating channels in the subchondral bone that allow revascularization to occur.

More advanced and unstable lesions with findings of edema beneath the fragment, subchondral cyst formation, and partial (see Fig. 718.3B) or complete (see Fig. 718.3C) fragment detachment on arthroscopy are potentially salvageable and should be treated surgically. Treatment involves drilling or fixation with possible bone grafting. OCD lesions may progress and become unstable and dislodge into the joint space (see Fig. 718.3D). Removal of the loose body in addition to cartilage repair and restoration are typically performed for unstable, unsalvageable lesions. In the postoperative period, patients usually require physical therapy to regain strength and range of motion, with a gradual return to baseline activity levels once full healing has been observed. Early identification and treatment of OCD lesions often prevents recurrent symptoms in adulthood and reduces the risk of early-onset osteoarthritis.

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718.4 Osgood-Schlatter Disease and Sinding-Larsen-Johansson Syndrome

Anne M. Coyle and J. Todd R. Lawrence

In skeletally immature patients, the tibial tubercle apophysis is an extension of the proximal tibial epiphysis. As the femur rapidly grows in length, patients often develop tight musculature, particularly of the quadriceps, across the knee joint. These patients also develop

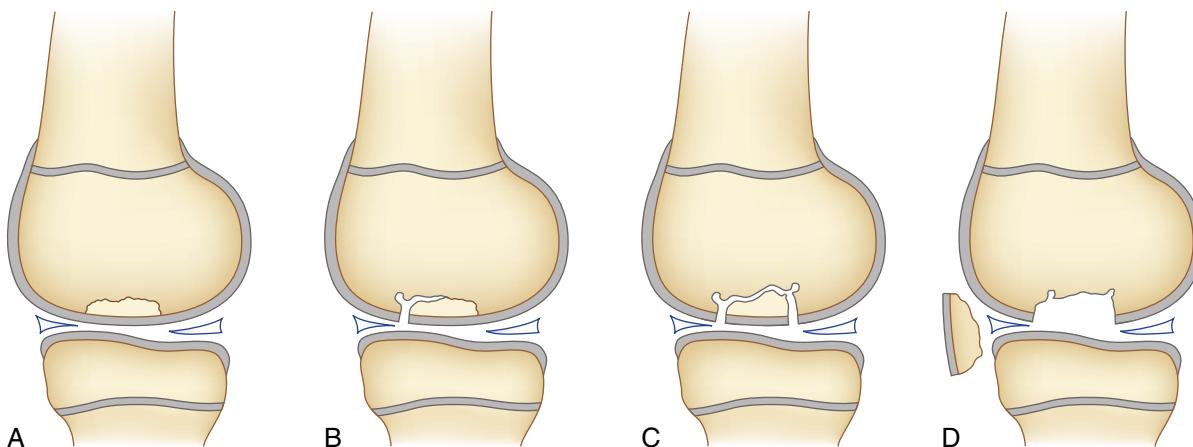


Fig. 718.3 The spectrum of osteochondritis dissecans (OCD) pathology of the knee. A, A stable and intact lesion without breach of the overlying articular cartilage. B, An OCD with fluid beneath the fragment, subchondral cyst formation, and partial fragment detachment. C, An unstable but located lesion with fluid beneath the fragment, multiple subchondral cysts, and complete fragment detachment. D, A dislodged OCD lesion, resulting in a loose body within the knee joint space.

movement patterns that preferentially place stress on the knees during physical activity instead of distributing that stress across other joints in the lower extremity. The repetitive tensile microtrauma sustained during sports or other athletic activities creates traction injuries at the weak points in the extensor mechanism at the knee, as the stress exceeds the developing skeleton's ability to repair the damage.

Sinding-Larsen-Johansson (SLJ) syndrome and **Osgood Schlatter (OS) disease** are *overuse injuries* that occur at the most common “weak points” in the system and are two of the most common causes of anterior knee pain in children and adolescents. SLJ syndrome is an **insertional periostitis** at the inferior pole of the patella. OS disease is an irritation of the patellar tendon at its insertion into the tibial tubercle or a **traction apophysitis** of the tibial tubercle growth plate. These conditions typically present during periods of relative accelerated growth and self-resolve within 12–24 months. SLJ syndrome tends to occur in a slightly younger patient population most commonly ages 9–13 years, whereas OS disease presents in slightly older patients with most symptomatic between the ages of 10–15 years. These conditions are most common in very physically active children particularly those that participate in sports such as basketball, volleyball, and soccer, in which jumping, kicking, and squatting puts repetitive strain on the patellar tendon.

CLINICAL MANIFESTATIONS AND DIAGNOSIS

Anterior knee pain, very specifically localized to the inferior pole of the patella (SLJ syndrome) or over the tibial tubercle (OS disease), is the most common patient complaint. Localized soft tissue swelling, along with an eventual firm and fixed increased prominence at the tibial tubercle, may occur with OS disease and may also be part of the initial complaint (Fig. 718.4). There is typically no acute traumatic inciting event, and the history of an acute traumatic onset of symptoms should raise the possibility of a tibial tubercle fracture or patellar sleeve fracture. The pain is aggravated by sports activities but may often persist with regular daily activities and even at rest. Physical examination reveals point tenderness over the inferior pole of the patella (SLJ) or over the tibial tubercle (OS disease). The presence of a knee effusion should raise the possibility of other intraarticular pathology. Diagnosis is usually made clinically, but radiographs may reveal fragmentation of the tibial tubercle and soft tissue swelling consistent with OS disease (Fig. 718.5) and be used to rule out other pathologies.

Another cause of patellar pain is **fat pad impingement syndrome** (Hoffa disease), which is characterized by inflammation and swelling of the infrapatellar fat pad, most often due to trauma or recent surgery. Patients may have pain when extending the knee against resistance.

TREATMENT

In most patients, SLJ syndrome and OS disease are self-limited processes and resolve with rest. Patients are treated with increasing levels

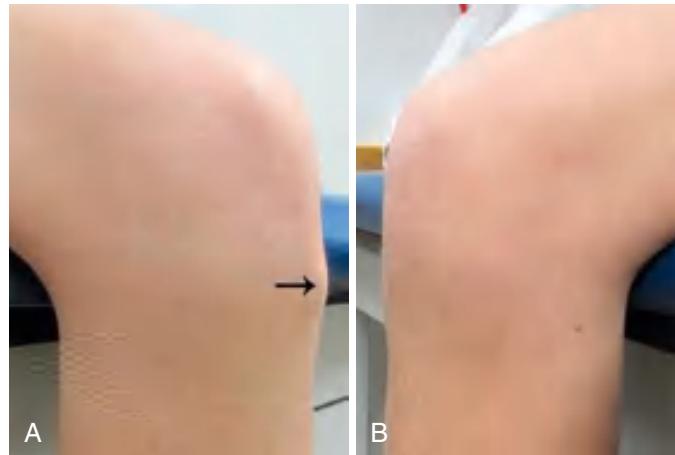


Fig. 718.4 Clinical manifestations of Osgood-Schlatter disease. The increased prominence of the tibial tubercle, indicated by the arrow, (A) from traction apophysitis in a 15-yr-old male's knee is contrasted with the normal appearance of the tibial tubercle (B) in his contralateral, unaffected knee.

of activity restriction or immobilization to get them to a pain-free state before advancing their activities. For instance, if they have pain only with running, but are pain free with normal daily activities, they may be restricted from running but perform daily activities for 2 weeks before advancing. In more severe cases, a knee immobilizer or even crutches with restricted weight-bearing are required to help the patient reach a pain-free state. Patients are usually advised to maintain this pain-free level of activity for 1–2 weeks before attempting to advance their activities. Sports and other dynamic activities are restricted until the patient is pain free with palpation and during daily activities for at least 2 weeks. During this rest period, addressing some of the contributing factors, such as muscular tightness, can help prevent a recurrence with activity resumption. A self-directed stretching regimen, concentrating on the quadriceps and hamstrings, may be provided. Some patients and resistant cases may benefit from formal instruction in these exercises with a physical therapist. Adjunctive therapy with ice (20 minutes every 2–4 hours and after activity) and NSAIDs (topical or oral) is common.

Communication with the patient and family members about the disease and prognosis is an important component of treatment. Reassurance may be appropriate because some patients and parents fear that the swollen tubercle may be a sign of a more significant pathology. Patients and family members should be advised that the tibial tubercle swelling will likely not fully resolve. Additionally, some evidence has suggested that a subgroup of patients who are competitive athletes may

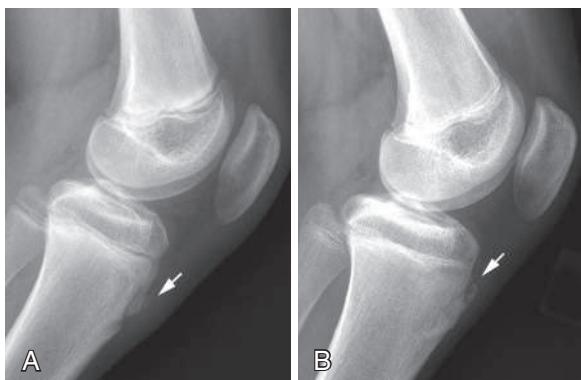


Fig. 718.5 Radiographic findings of Osgood-Schlatter disease. A, Lateral radiograph of the knee of a 13-yr-old male demonstrates a sliver of new bone formation (arrow) at the tibial tubercle. B, Lateral radiograph of the same child at 15 yr of age demonstrates characteristic fragmentation (arrow) of the tibial tubercle.

experience long-term pain, and therefore options of treatment strategies and goals regarding participation in competitive sports may need to be discussed.

Treatment with hyperosmolar dextrose local injections may improve outcomes in patients with recalcitrant OS disease. However, corticosteroid injections are not recommended because of the risk of rupture of the patellar tendon due to steroid-induced atrophy. In the rare situation in which young adults have persistent and disabling symptoms, surgical removal of ossicles from the tubercle or reduction of an enlarged tibial tubercle may be warranted. Complications are rare and include early closure of the tibial tubercle with recurvatum or hyperextension, deformity, and, rarely, patellar tendon rupture or avulsion fracture of the tibial tubercle. Although rare, these complications can have significant long-term consequences and should thus prompt counseling to avoid playing through the pain.

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718.5 Patellofemoral Pain Syndrome

Anne M. Coyle and J. Todd R. Lawrence

Also known as **anterior knee pain syndrome**, patellofemoral pain syndrome (PFPS) is one of the most common causes of knee pain and is characterized by pain located around or behind the patella that is elicited during activities that load the patella during knee flexion and weight-bearing such as squatting and running. PFPS affects 6–7% of the general adolescent population and up to 25% of teens who participate in sports. Females are estimated to account for 55–62% cases. Previously, PFPS was thought to arise from a deranged patellar articular surface; however, increasing evidence shows that anterior knee pain is frequently present even with normal articular cartilage of the patella. Even though abnormal patellar tracking may have a role in the pathogenesis, the precise etiology of the knee pain remains unknown and is likely multifactorial. In adolescents, repetitive loading of the knee joint without adequate time for recovery is thought to be a key factor in developing PFPS.

CLINICAL MANIFESTATIONS AND DIAGNOSIS

Pain is usually described as being beneath or near the patella. The pain is worse with bent knee activities, such as walking up and down stairs, because these activities put the patella under high compressive loads. Squatting, running, and other vigorous physical activities also exacerbate the anterior knee pain. Sitting in a flexed knee position for an extended period of time, the so-called **theater sign**, is another common complaint and is often relieved through knee extension. The onset of symptoms is usually gradual, with no history of trauma. If a traumatic etiology is noted, consideration for other etiologies should be

entertained. Buckling or a sense of the knee *giving way* can occur, but there is rarely any true patellar or knee instability. Swelling is not common and, if present, should prompt further investigation.

On physical examination, reproduction of the patient's pain with palpation about the medial or lateral aspects of the patella and pain during squatting have the highest sensitivity for PFPS. With the knee extended and the quadriceps relaxed, placing pressure on the patella and translating it distally into the top of the trochlear groove, the **grind test**, often also causes pain. Two tests, the patellar tilt test and the patellar apprehension test, have been found to have low sensitivity but the highest specificity for PFPS. The **patellar tilt test** is performed while holding the patella between two fingers, and with the knee extended, the medial patella is compressed posteriorly while simultaneously trying to elevate the lateral aspect of the patella. A fixed lateral aspect of the patella indicates tight lateral structures. With the **patellar apprehension test**, there is resistance to forced lateral displacement of the patella. Reproduction of the patient's pain with these maneuvers is an important component of the examination. Active and passive range of motion of the knee, alignment of the lower extremity, knee ligamentous stability, patellar tracking, and gait should be evaluated to identify any obvious causes of malalignment or an unstable patella. These patients often have tight quadriceps, hamstrings, and heel cords, along with weak hip musculature and poor overall balance. A single leg squat can often highlight the hip weakness and balance and alignment issues that contribute to this condition.

Radiographs are not required for diagnosis as there are no structural defects in PFPS; however, routine radiographs of the knee, including AP, lateral, tunnel (PA with 45-degree flexed knee), and merchant (patellar) views, are sometimes obtained to eliminate other etiologies of vague knee pain, such as OCD. Radiographs of the hip should be considered to rule out hip pathology, such as a slipped capital femoral epiphysis, which can manifest as ill-defined knee pain in adolescents as well. An MRI is not routinely required for evaluation but should be considered in any patient with a history of mechanical symptoms or an effusion. MRI should be considered in cases refractory to standard treatments as well.

TREATMENT

Several methods of nonoperative treatment are used to address PFPS. The mainstay of treatment is continued physiotherapy, involving overall lower-extremity stretching and strengthening, including short-arc quadriceps strengthening, hip and core strengthening, and exercises designed to address balance and overall body positioning during dynamic activities. Home exercise programs can be effective for the properly disciplined and motivated patient, but formal physical therapy should be considered in resistant cases or in patients who are unable to adhere to a self-directed program. Combining physiotherapy with activity modification and load management during treatment is associated with an increased rate of return to sports. Orthoses, including patellar taping, knee sleeves, customized knee braces, or even shoe inserts are often used in conjunction with physical therapy. Knee taping alone does not improve pain; however, exercise therapy in combination with knee taping has a greater reduction in pain than exercise therapy alone. Evidence for long-term benefit from other orthotic use is unclear. Treatment with botulinum toxin injections, nonsteroidal antiinflammatory medications, or therapeutic ultrasound is not substantiated. Despite these efforts, 40% of adolescents will have some pain that continues into early adulthood and significantly affects their quality of life, knee function, and physical activity. Surgical treatment of PFPS is rarely necessary.

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718.6 Patellofemoral Instability

Anne M. Coyle and J. Todd R. Lawrence

The stable tracking of the patellofemoral joint in the front of the knee depends on a balance of the static restraints and the dynamic forces

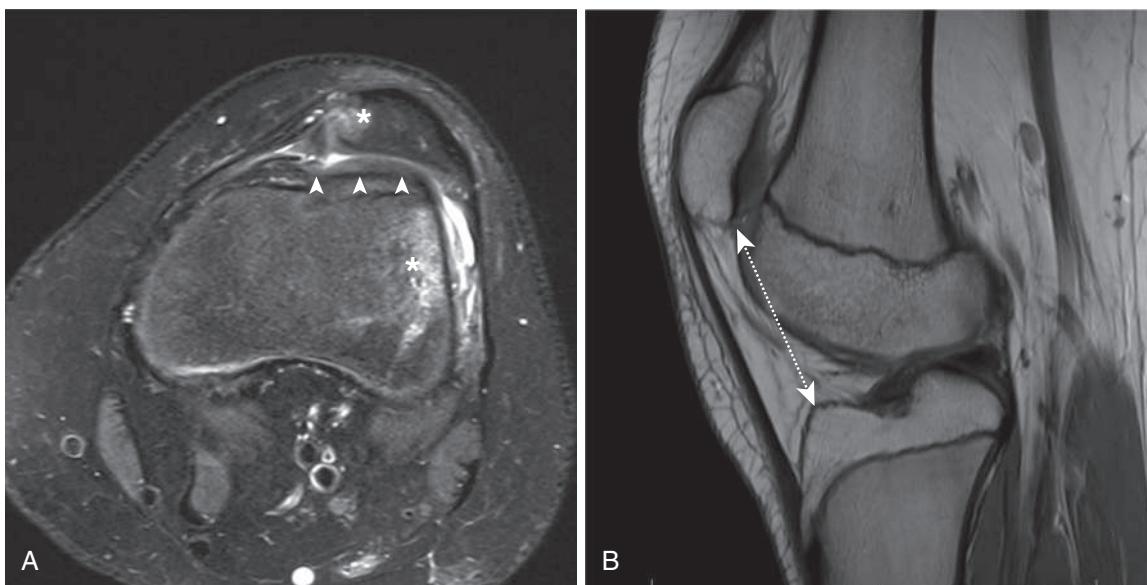


Fig. 718.6 A 14-yr-old female with patellar instability. **A**, A T2-weighted fat suppression axial image through the mid-patella and proximal trochlea demonstrates the characteristic bone bruise pattern on the medial patella and along the lateral femoral condyle that occurs when the dislocated medial patella impacts the lateral femur (asterisks). Injury to the patellar attachment of the medial patellofemoral ligament is also visible at the medial patella. The patella is laterally subluxated in a dysplastic trochlea that is flat to slightly convex (arrowheads) instead of having a normal concave shape. **B**, A proton density weighted sagittal image through the center of the knee and patella demonstrates patella alta, with the distance from the anterior tibia to the inferior aspect of the patellar cartilage (dotted line) being much longer than the length of the patellar cartilage.

acting on the patella. These include the restraining ligaments and the articular anatomy of the patellofemoral groove that serve to balance the dynamic forces of the quadriceps mechanism and overall limb positioning. During knee flexion, the pull of the quadriceps mechanism tends to place an overall lateral displacing force at the patella. The **Q angle** refers to the deviation between the angle of the patellar tendon and the line of the quadriceps. Wider hips and valgus (knock-knee) positioning increase the Q angle and thus the lateral force applied at the patella. In extension, the static restraints, including the medial restraining ligaments, primarily the medial patellofemoral ligament, are responsible for guiding the patella into the trochlear groove in the distal femur. Once in the trochlea, the bony congruity becomes the primary restraint to the net lateral forces.

Factors that contribute to patellofemoral instability are multifactorial, including ligamentous laxity; trochlear dysplasia, creating a shallow sulcus; condylar hypoplasia; patella alta (a high-riding patella); or malalignment that effectively increases the Q angle, such as genu valgum, increased femoral anteversion, or a lateralized tibial tubercle.

Acute patellofemoral dislocation is the most common acute knee disorder in children and adolescents between ages 10-19 years and often occurs after a sudden valgus strain during sports participation, but it may also be the result of direct trauma. **Recurrent patellofemoral subluxation** is more than one episode of patellar subluxation without frank dislocation. Lateral malalignment of the extensor mechanism and trochlear dysplasia are the most common etiologic factors. **Habitual dislocation of the patella** describes patellar dislocation occurring during every knee flexion/extension cycle. A dysplastic knee with contracture of the lateral portion of the quadriceps mechanism is often associated. Several syndromes are associated with patellar instability, including Down syndrome (see Chapter 57), Turner syndrome (see Chapter 626.1), Kabuki syndrome (see Chapter 102.2), and Rubinstein-Taybi syndrome (see Chapter 102.3).

CLINICAL MANIFESTATIONS AND DIAGNOSIS

With an **acute patellar dislocation**, patients will recall the acute event and the sensation that their kneecap was out of place. A focused, detailed history is important for characterizing the instability. Straightening the knee is all that is usually required to reduce the patella, but sometimes this requires medical attention. Swelling is typically apparent immediately after the injury and appreciable on examination as

a large effusion. Pain along the knee from the medial patella to the medial epicondyle of the femur is common. Lateral patellar translocation with the knee extended should be tested with the **patellar apprehension test**. In the acute setting, there will be increased translation and pain and a feeling of insecurity. Patellar tracking is also an important component of the examination but may not be possible due to pain in the acute setting. The **J sign** refers to the inverted J-path the patella takes, beginning in a laterally subluxated position and then suddenly shifting medially to engage the femoral groove with early knee flexion. The torsional profile of the extremity is also important to assess to rule out possible rotational abnormalities of the femur or tibia.

Radiographs of a patient with patellar instability should include AP, lateral, and merchant views (obtained with the knee bent 45 degrees, with the beam of the x-ray through the knee from head to toe) of the patella. In children and adolescents with acute patellar dislocations, osteochondral injuries are present in up to 75% of cases. Radiographs should also be carefully examined for occult fractures. In the presence of a significant knee effusion, mechanical symptoms, acute traumatic patellar dislocation, or uncertainty in the diagnosis, further investigation should include an MRI to evaluate for loose bodies or cartilage damage. MRI will demonstrate bone bruise patterns typical of patellar dislocation at the medial patellar facet and at the lateral femoral condyle and a tear in the medial patellofemoral ligament (Fig. 718.6). Risk factors for recurrent instability include skeletal immaturity, ligamentous laxity, patella alta (see Fig. 718.6), trochlear dysplasia (see Fig. 718.6), and lateralized tibial tubercle (particularly one situated outside the lateral trochlear ridge).

TREATMENT

Nonoperative management that includes activity restriction, bracing, and physical therapy with return to full activity within 3-4 months is initially recommended for first-time, acute patellar dislocation and recurrent patellar subluxation, unless a large osteochondral fracture or additional intraarticular pathology is seen on imaging studies. Short-term immobilization for 3 weeks in extension with a posterior splint has been shown to significantly decrease the risk of redislocation. After this, transition to a patellar stabilizing brace usually improves symptoms. Successful treatment is usually achieved with formal physical therapy aimed at improving extensor muscle tone, particularly the vastus medialis obliquus, activity-related body positioning, stretching the iliotibial band, and hip and core

muscle strengthening. Current criteria to return to full activity after conservative management requires absence of pain, recurring patellar instability, and knee effusion, as well as full range of motion, adequate core strength and endurance, psychologic readiness, hop test showing limb symmetry >85%, and satisfactory performance on sport-specific drills. Recurrent, ipsilateral patellofemoral instability is reported in up to 36% of skeletally mature patients. However, the reported redislocation rate in skeletally immature patients is as high as 69%. Risk factors for recurrence include younger age at time of first dislocation, ligamentous laxity, open physes, trochlear dysplasia (shallow trochlea), and extensor mechanism malalignment. Patients at high risk for recurrent dislocation may elect to undergo surgical stabilization early to prevent additional traumatic cartilage damage from a repeat dislocation, but early stabilization after the first dislocation is not currently a mainstay of treatment.

Failure to improve after nonoperative treatment and persistent patellar subluxation or experiencing a recurrent dislocation are the major indications for surgical intervention. Patients are considered surgical candidates for early intervention if there are loose bodies, osteochondral fractures, or chondral damage to prevent mechanical blocking of motion. Many different types of surgical procedures exist to prevent dislocation of the patella, but almost all include reconstruction of the medial patellofemoral ligament. Distal realignment of the patellar tendon insertion with a tibial tubercle osteotomy can help improve overall alignment and is often included as part of the stabilization procedure in skeletally mature adolescents. In skeletally immature patients, surgical reconstruction with physeal-sparing techniques can be performed. Guided growth techniques can be used in patients with growth remaining (typically 6 months–1 year) to correct overall alignment. The surgical approach should be patient specific depending on the pathoanatomy contributing to the recurrent instability for best outcomes. Return to full activity criteria is similar to that for nonsurgical management but the timeline may be adjusted based on underlying pathology and bone healing. Recurrence of patellofemoral instability after surgical intervention is estimated to be around 20%.

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718.7 Anterior Cruciate Ligament Rupture

Anne M. Coyle and J. Todd R. Lawrence

Anterior cruciate ligament (ACL) tears account for more than half of all knee injuries. Young age is a known risk factor with peak incidence at 16–18 years old. Pediatric ACL reconstruction has become more prevalent as ACL tears in skeletally immature patients have greatly increased in recent years. This increase is likely due to increased sports participation, increased intensity of training and competition, and participation on multiple teams. Heightened awareness and improved methods for diagnosis are also likely contributing factors to the growing awareness of ACL injuries in children and adolescents.

Females are known to have up to a twofold increased risk for ACL injury compared to males playing the same sport. The gender-specific discrepancy appears to be caused mostly by insufficient neuromuscular activation patterns in females, resulting in increased dynamic **genus valgum** (knock-knee), biased limb alignment when landing, and therefore a heightened tendency toward landing or stopping in an injury-prone position. Other nonmodifiable risk factors include generalized joint laxity, knee recurvatum (hyperextension), femoral anteversion, and contralateral ACL injury. Various pediatric ACL injury prevention programs have shown benefits in not only reducing the rate of injuries but also in increasing athletic strength and performance. Studies also indicate that universal implementation of injury prevention programs can be a cost-effective prevention strategy.

CLINICAL MANIFESTATIONS AND DIAGNOSIS

Most ACL tears occur as a result of a noncontact injury involving a rapid pivoting, cutting, landing, or stopping maneuver. Patients with an acute knee injury from one of these activities who present with

knee effusion and report a “pop” have a 70% chance of an ACL tear. The pop sensation occurs at the time of injury with later development of swelling, limited range of motion, and sometimes a sensation of instability. After the initial injury, patients may have surprisingly little pain. On physical examination, the **anterior drawer sign** or **Lachman test** may indicate increased anterior tibial translation. The Lachman examination is performed by applying an anteriorly directed force to the proximal tibia with the femur stabilized and the knee flexed 20–30 degrees. The amount of translation and the end point are assessed, with increased translation and an indistinct end point indicating a positive test. A **pivot shift test** can also be performed to confirm the diagnosis, but it is rarely tolerated in the conscious patient. It is conducted by gently bending the knee while just supporting the lower leg. A gentle valgus stress and slight internal rotation can enhance the shift. Assessment for concurrent injury to the medial collateral ligament and medial or lateral menisci should be considered as concurrent tears can be present in up to 45% of ACL tears.

Radiographs of the knee are performed, including AP, lateral, tunnel (PA with 45 degrees flexed knee), and merchant (patellar) views, to assess for other potential injuries common in pediatric and adolescent patients, such as tibial spine avulsion fractures or OCD. In acute traumatic injuries, internal and external oblique radiographs can also be helpful. Ultimately, knee MRI is usually necessary to confirm the presence of an intrasubstance ACL tear and any associated meniscal or chondral pathology (Fig. 718.7). Arthroscopic evaluation is the gold standard for diagnosis and treatment.

TREATMENT

The management of ACL injury in this patient population can be challenging, and the severity of the ACL tear and the degree of knee instability are important in directing treatment. Incomplete or partial ACL tears with a firm endpoint on examination may be treated nonoperatively, and the patient's and family's understanding and willingness to adhere to a protocol of bracing and activity restriction are important factors in optimizing outcomes. For complete tears of the ACL, surgical reconstruction is the preferred treatment for patients who are physically, mentally, and emotionally capable of maintaining precautions and complying with the long rehabilitation course after the procedure. Increasing evidence suggests that optimal timing for surgical intervention is within 3 months of injury to reduce the likelihood of additional damage occurring in the knee. While timing does not seem to affect recovery of knee stability, the risk of meniscal injury is up to 4.5 times higher when surgical intervention is delayed. Use of autologous tissue for ACL reconstruction is usually recommended for young active patients due to a lower risk of reinjury compared to allograft tissue. Growth-respecting ACL reconstruction techniques, such as all-epiphyseal, partial transphyseal, or traditional transphyseal reconstruction techniques, are used based on the skeletal maturity of the patient to minimize the risk for growth disturbance across the distal femoral and proximal tibial physes. The ultimate treatment course is an individual decision for the patient and family to make in consultation with their physician.

Depending on the technique used for reconstruction and any associated meniscal pathology addressed, weight-bearing is initially restricted, and a brace is used for the first 4–6 weeks postoperatively. Physical therapy is started postoperatively and continued until strength and functional testing are equal to the contralateral, unaffected limb. Injury prevention through neuromuscular training is built into the final phases of the rehabilitation and final screening tests to try to minimize the risk of reinjury. Most patients regain full range of motion and report no pain by 12 weeks after surgery. Patients return to sports typically at a minimum of 9–12 months postoperatively and are followed on a yearly basis thereafter until skeletal maturity to monitor progress and for any signs of growth disturbance. The majority of athletes are able to return to their same level of competition. The role of using a brace following ACL reconstruction is not established. Rehabilitation programs focused on strengthening, proximal control exercises, and incorporation of various exercise genres have significantly reduced the recurrence in female athletes. However, despite extensive prevention

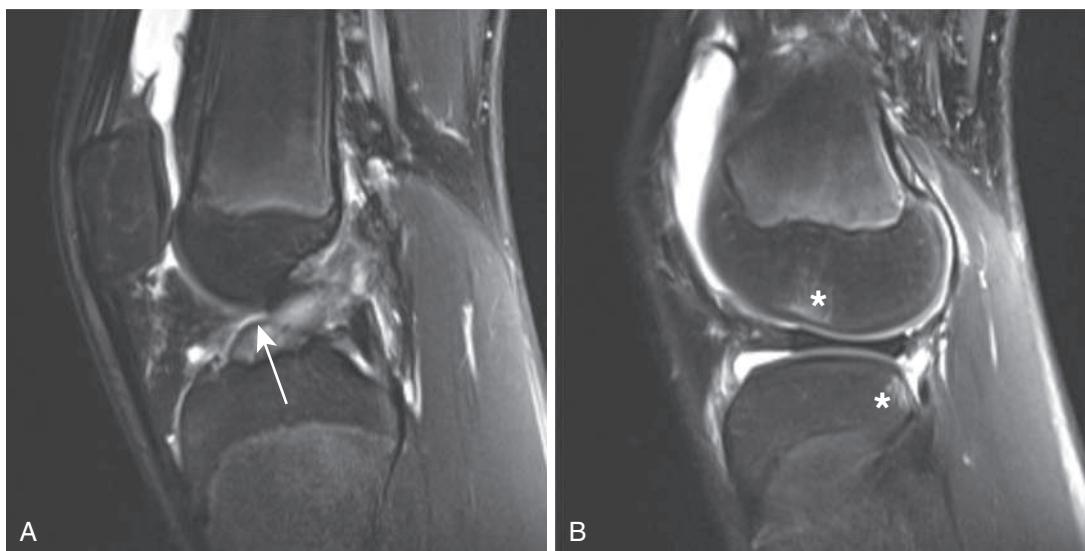


Fig. 718.7 A 14-yr-old female with full-thickness anterior cruciate ligament (ACL) tear. **A**, A T2-weighted fat-suppression sagittal image through the center of the knee demonstrates a full-thickness tear of the ACL with a folded stump near the tibial attachment. (arrow). **B**, A T2-weighted fat-suppression sagittal image through the lateral compartment demonstrates the characteristic kissing contusion pattern in the distal femoral condyle and posterior tibial plateau related to the anterior pivot shift that occurs during the ACL injury (asterisks).

efforts, secondary injury rates within 24 months of ACL reconstruction remain very high when patients elect to return to risky sports. The sports with the greatest risk for ACL tears are soccer, basketball, and lacrosse for females and football, soccer, and lacrosse for males. Revision of ACL reconstructions has been associated with increased complications.

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Chapter 719

The Hip

Wudbhav N. Sankar, Jennifer J. Winell,
B. David Horn, and Lawrence Wells

Anatomically, the hip joint is a ball-and-socket articulation between the femoral head and acetabulum. The hip joint is a pivotal joint of the lower extremity, and its functional demands require both stability and flexibility.

GROWTH AND DEVELOPMENT

The hip joint begins to develop at about the seventh week of gestation, when a cleft appears in the mesenchyme of the primitive limb bud. These precartilaginous cells differentiate into a fully formed cartilaginous **femoral head** and **acetabulum** by the eleventh week of gestation (see Chapter 21). At birth, the neonatal acetabulum is completely composed of cartilage, with a thin rim of fibrocartilage called the **labrum**.

The very cellular hyaline cartilage of the acetabulum is continuous with the triradiate cartilages, which divide and interconnect the three osseous components of the pelvis (the **ilium**, **ischium**, and **pubis**). The concave shape of the hip joint is determined by the presence of a spherical femoral head.

Several factors determine acetabular depth, including interstitial growth within the acetabular cartilage, appositional growth under the perichondrium, and growth of adjacent bones (the ilium, ischium, and pubis). In the neonate, the entire proximal femur is a cartilaginous structure, which includes the femoral head and the greater and lesser trochanters. The three main growth areas are the physeal plate, the growth plate of the greater trochanter, and the femoral neck isthmus. Between the fourth and seventh month of life, the proximal femoral ossification center (in the center of the femoral head) appears. This ossification center continues to enlarge, along with its cartilaginous anlage, until adult life, when only a thin layer of articular cartilage remains. During this period of growth, the thickness of the cartilage surrounding this bony nucleus gradually decreases, as does the thickness of the acetabular cartilage. The growth of the proximal femur is affected by muscle pull, the forces transmitted across the hip joint with weight bearing, normal joint nutrition, circulation, and muscle tone. Alterations in these factors can cause profound changes in the development of the proximal femur.

VASCULAR SUPPLY

The blood supply to the capital femoral epiphysis is complex and changes with growth of the proximal femur. The proximal femur receives its arterial supply from intraosseous (primarily the medial femoral circumflex artery) and extraosseous vessels (Fig. 719.1). The **retinacular vessels** (extraosseous) lie on the surface of the femoral neck but are intracapsular because they enter the epiphysis from the periphery. This makes the blood supply vulnerable to damage from septic arthritis, trauma, thrombosis, and other vascular insults. Interruption of this tenuous blood supply can lead to avascular necrosis of the femoral head and permanent deformity of the hip.

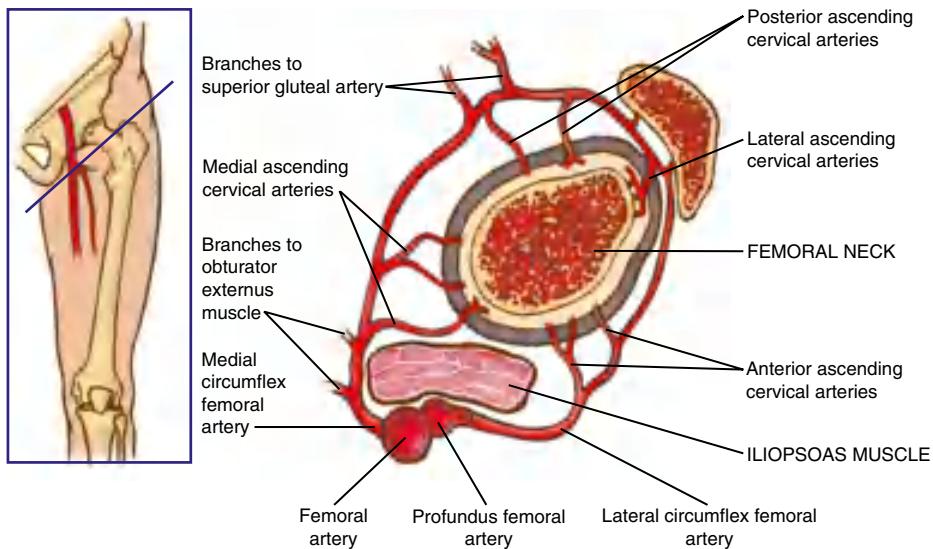


Fig. 719.1 Diagram of vascular anatomy of the proximal femur.

719.1 Developmental Dysplasia of the Hip

Wudbhav N. Sankar, B. David Horn, Jennifer J. Winell, and Lawrence Wells

Developmental dysplasia of the hip (DDH) refers to a spectrum of pathology in the development of the immature hip joint. Formerly called *congenital dislocation of the hip*, DDH more accurately describes the variable presentation of the disorder, encompassing mild dysplasia as well as frank dislocation.

CLASSIFICATION

Acetabular **dysplasia** refers to abnormal morphology and development of the acetabulum. Hip **subluxation** is defined as only partial contact between the femoral head and acetabulum. Hip **dislocation** refers to a hip with no contact between the articulating surfaces of the hip. DDH is classified into two major groups: typical and teratologic. **Typical DDH** occurs in otherwise normal patients or those without defined syndromes or genetic conditions. **Teratologic hip dislocations** usually have identifiable causes, such as arthrogryposis or a genetic syndrome, and occur before birth.

ETIOLOGY AND RISK FACTORS

Although the etiology remains unknown, the final common pathway in the development of DDH is increased laxity of the joint, which fails to maintain a stable femoroacetabular articulation. This increased laxity is probably the result of a combination of hormonal, mechanical, and genetic factors. A positive family history for DDH is found in 12–33% of affected patients. DDH is more common among female patients (80%), which is thought to be because of the greater susceptibility of female fetuses to maternal hormones, such as relaxin, which increases ligamentous laxity. Although only 3–4% of all babies are born in breech presentation, the incidence of DDH in these patients is 16–25%.

Any condition that leads to a tighter intrauterine space and, consequently, less room for normal fetal motion may be associated with DDH. These conditions include oligohydramnios, large birth weight, and first pregnancy. The high rate of association of DDH with other intrauterine molding abnormalities, such as torticollis and metatarsus adductus, supports the theory that the *crowding phenomenon* has a role in the pathogenesis. The left hip is the most commonly affected hip. In the most common fetal position, the left hip is usually forced into adduction by the mother's sacrum.

Tight swaddling with the hips in the extended position has been identified as an important risk factor for the development of hip dysplasia. Population studies of cultures that prefer immobilizing children in hip extension have shown that swaddling in such a way that prevents an infant from naturally drawing their hips to their chest (so called "M" position) is detrimental for hip development.

EPIDEMIOLOGY

Although most newborn screening studies suggest that some degree of hip instability can be detected in 1 in 100 to 1 in 250 babies, actual dislocated or dislocatable hips are much less common, being found in 1–1.5 of 1,000 live births.

There is marked geographic and racial variation in the incidence of DDH. These differences may result from environmental factors, such as child-rearing practices, rather than genetic predisposition. African and Asian caregivers have traditionally carried babies against their bodies in a shawl so that a child's hips are flexed, abducted, and free to move. This keeps the hips in the optimal position for stability and for dynamic molding of the developing acetabulum by the cartilaginous femoral head. Children in Native American and Eastern European cultures, which have a relatively high incidence of DDH, have historically been swaddled in confining clothes that bring their hips into extension. This position increases the tension of the psoas muscle-tendon unit and might predispose the hips to displace and eventually dislocate laterally and superiorly.

PATHOANATOMY

In DDH, several secondary anatomic changes can prevent reduction. Both the fatty tissue in the depths of the socket, known as the pulvinar, and the ligamentum teres can hypertrophy, blocking reduction of the femoral head. The transverse acetabular ligament usually thickens as well, which effectively narrows the opening of the acetabulum. In addition, the shortened iliopsoas tendon becomes taut across the front of the hip, creating an hourglass shape to the hip capsule, which limits access to the acetabulum. Over time, the dislocated femoral head places pressure on the acetabular rim and labrum, causing the labrum to infold and become thick.

The shape of a normal femoral head and acetabulum depends on a concentric reduction between the two. The more time that a hip spends dislocated, the more likely that the acetabulum will develop abnormally. Without a femoral head to provide a template, the acetabulum will become progressively shallow, with an oblique acetabular roof and a thickened medial wall.

CLINICAL FINDINGS

The Neonate

DDH in the neonate is asymptomatic and must be screened for in all newborns by specific maneuvers. Physical examination must be carried out with the infant unclothed and placed supine in a warm, comfortable setting on a flat examination table.

The **Barlow** provocative maneuver assesses the potential for dislocation of an initially nondisplaced hip. The examiner adducts the flexed hip and gently pushes the thigh posteriorly in an effort to dislocate the femoral head (Fig. 719.2). In a positive test, the hip is felt to slide out of the acetabulum. As the examiner relaxes the proximal push, the hip can be felt to slip back into the acetabulum.

The **Ortolani** test is the reverse of the Barlow test: The examiner attempts to reduce a hip that is dislocated at rest (Fig. 719.3). The examiner grasps the child's thigh between the thumb and index finger and, with the fourth and fifth fingers, lifts the greater trochanter while simultaneously abducting the hip. When the test is positive, the femoral head will slip into the socket with a delicate clunk that is palpable but usually not audible. It should be a gentle, nonforced maneuver.

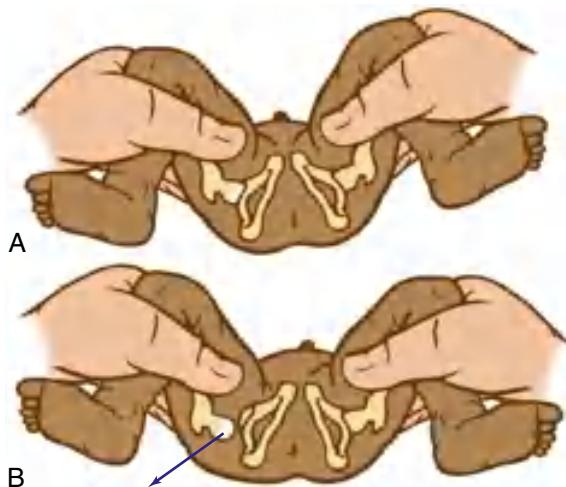


Fig. 719.2 The Barlow provocative test is performed with the patient's knees and hips flexed. A, Holding the patient's limbs gently, with the thigh in adduction, the examiner applies a posteriorly directed force. B, This test is positive in a dislocatable hip.

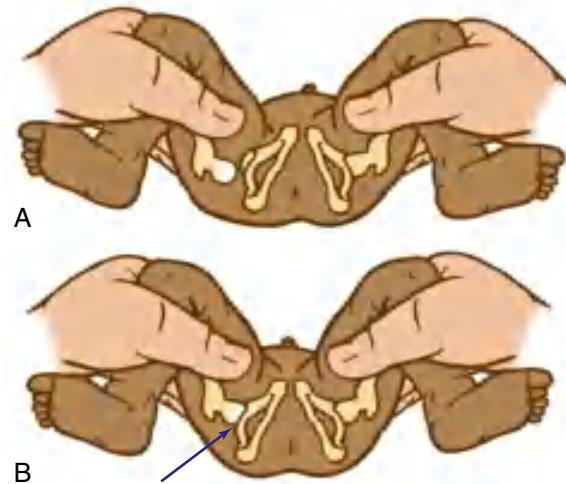


Fig. 719.3 The Ortolani maneuver is the sign of the ball of the femoral head moving in and out of the acetabulum. A, The examiner holds the patient's thigh and gently abducts the hip while lifting the greater trochanter with two fingers. B, When the test is positive, the dislocated femoral head falls back into the acetabulum with a palpable clunk as the hip is abducted.

A **hip click** is the high-pitched sensation (or sound) felt at the very end of abduction during testing for DDH with Barlow and Ortolani maneuvers. A hip click can be differentiated from a **hip clunk**, which is felt as the femoral head goes in and out of joint. Hip clicks usually originate in the ligamentum teres or occasionally in the fascia lata or psoas tendon and do not indicate a significant hip abnormality.

The Infant

As the baby enters the second and third month of life, the soft tissues begin to tighten, and the Ortolani and Barlow tests are no longer reliable. In this age-group, the examiner must look for other specific physical findings, including limited hip abduction, apparent shortening of the thigh, proximal location of the greater trochanter, asymmetry of the gluteal or thigh folds (Fig. 719.4), and positioning of the hip. Limitation of abduction is the most reliable sign of a dislocated hip in this age-group.

Shortening of the thigh, the **Galeazzi sign**, is best appreciated by placing both hips in 90 degrees of flexion and comparing the height of the knees, looking for asymmetry (Fig. 719.5). Asymmetry of gluteal skin creases may be a sign of hip dysplasia. Another helpful test is the **Klasic test**, in which the examiner places the third finger over the greater trochanter and the index finger of the same hand on the anterior superior iliac spine. In a normal hip, an imaginary line drawn between the two fingers points to the umbilicus. In the dislocated hip, the trochanter is elevated, and the line projects halfway between the umbilicus and the pubis (Fig. 719.6).



Fig. 719.4 Asymmetry of thigh folds in a child with developmental dysplasia of the hip.



Fig. 719.5 Positive Galeazzi sign noted in a case of untreated developmental dysplasia of the hip.

The Walking Child

The walking child often presents to the physician after the family has noticed a limp, a waddling gait, or a leg-length discrepancy. The affected side appears shorter than the normal extremity, and the child toe-walks on the affected side. The **Trendelenburg sign** (see Chapter 714) is positive in these children, and an abductor lurch is usually observed when the child walks. As in the younger child, there is limited hip abduction on the affected side and the knees are at different levels when the hips are flexed (the Galeazzi sign). Excessive lordosis, which develops secondary to altered hip mechanics, is common and is often the presenting complaint.

DIAGNOSTIC TESTING

Ultrasonography

Because it is superior to radiographs for evaluating cartilaginous structures, ultrasonography is the diagnostic modality of choice for DDH before the appearance of the femoral head ossific nucleus (4–6 months). During the early newborn period (0–4 weeks), however, physical examination is preferred over ultrasonography because there is a high incidence of false-positive sonograms in this age-group. Therefore, waiting to obtain an ultrasound until the infant is at least 6 weeks of age is recommended unless the child has a strongly positive physical examination. In addition to elucidating the static relationship of the femur to the acetabulum, ultrasonography provides dynamic information about the stability of the hip joint. The ultrasound examination can be used to

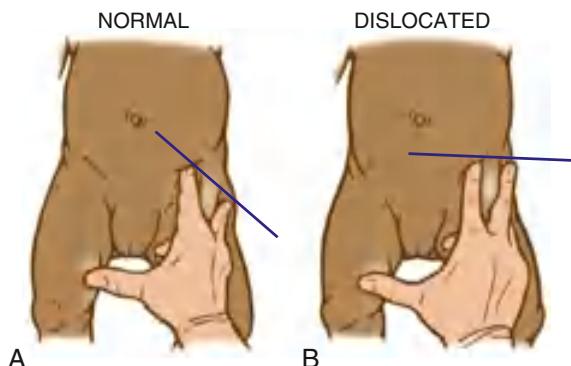


Fig. 719.6 Klisic test. A, In a normal hip, an imaginary line drawn down through the tip of an index finger placed on the patient's iliac crest and the tip of the long finger placed on the patient's greater trochanter should point to the umbilicus. B, In a dislocated hip, this line drawn through the two fingertips runs below the umbilicus because the greater trochanter is abnormally high.

monitor acetabular development, particularly of infants in Pavlik harness treatment; this method can minimize the number of radiographs taken and might allow the clinician to detect treatment failure earlier.

In the Graf technique, the transducer is placed over the greater trochanter, which allows visualization of the ilium, the bony acetabulum, the labrum, and the femoral epiphysis (Fig. 719.7). The angle formed by the line of the ilium and a line tangential to the bony roof of the acetabulum is termed the α angle and represents the depth of the acetabulum. Values >60 degrees are considered normal, and those <60 degrees imply acetabular dysplasia. The β angle is formed by a line drawn tangential to the labrum and the line of the ilium; this represents the cartilaginous roof of the acetabulum. A normal β angle is <55 degrees; as the femoral head subluxates, the β angle increases. Another useful test is to evaluate the position of the center of the head compared with the vertical line of the ilium. If the line of the ilium falls lateral to the center of the head, the epiphysis is considered reduced. If the line falls medial to the center of the head, the epiphysis is uncovered and is either subluxated or dislocated.

Screening for DDH with ultrasound remains controversial. Although routinely performed in Europe, meta-analyses indicate that data are insufficient to give clear recommendations. In the United States, the current recommendations are that every newborn undergo a clinical examination for hip instability. Children who have findings suspicious for DDH should be followed up with ultrasound. Most authors agree that infants with risk factors for DDH (breech position, family history, torticollis) should be screened with ultrasound regardless of the clinical findings.

Radiography

Radiographs are recommended for an infant once the proximal femoral epiphysis ossifies, usually by 4–6 months. In infants of this age, radiographs have proven to be more effective, less costly, and less operator dependent than an ultrasound examination. An anteroposterior (AP) view of the pelvis can be interpreted with the aid of several classic lines drawn on it (Fig. 719.8).

Hilgenreiner's line is a horizontal line drawn through the top of both triradiate cartilages (the clear area in the depth of the acetabulum). **Perkins line** is a vertical line through the most lateral ossified margin of the roof of the acetabulum, drawn perpendicular to Hilgenreiner's line. The ossific nucleus of the femoral head should be located in the medial lower quadrant of the intersection of these two lines. **Shenton's line** is a curved line drawn from the medial aspect of the femoral neck to the lower border of the superior pubic ramus. In a child with normal hips, this line is a continuous contour. In a child with hip subluxation or dislocation, this line consists of two separate arcs and is described as "broken."

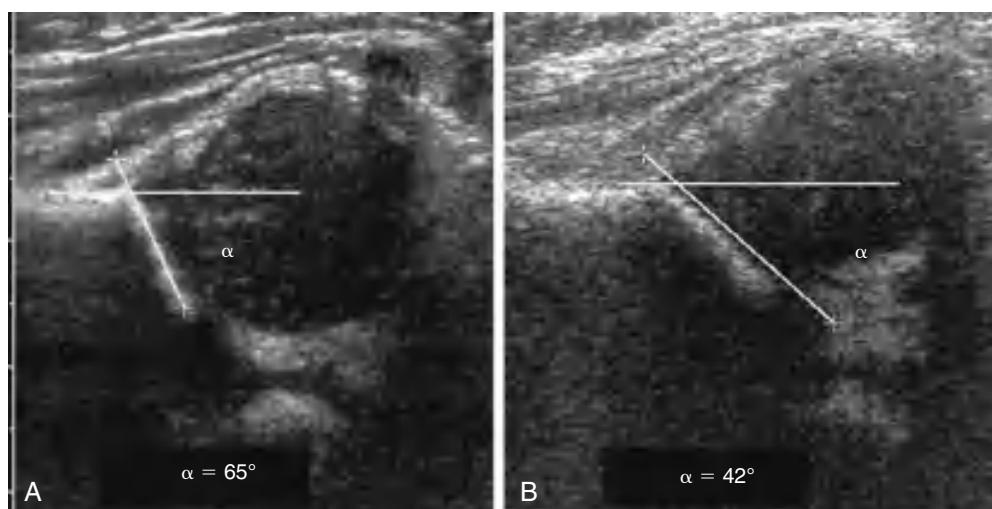


Fig. 719.7 A, Normal ultrasonographic image of the hip in an infant. The α angle is >60 degrees. Note that a line drawn tangential to the ilium falls lateral to the center of the femoral head. B, In this child with developmental dysplasia of the hip, the left hip demonstrates an α angle of 42 degrees, and a line drawn tangential to the ilium shows that <50% of the femoral head is contained within the acetabulum.

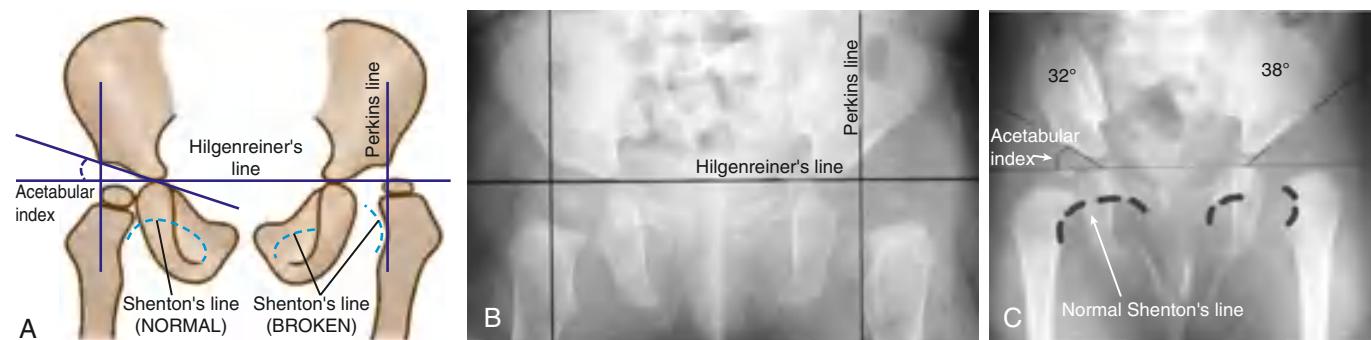


Fig. 719.8 A-C, Radiographic measurements are useful in evaluating developmental dysplasia of the hip. Hilgenreiner's line is drawn through the triradiate cartilages. Perkins line is drawn perpendicular to Hilgenreiner's line at the lateral edge of the acetabulum. The ossific nucleus of the femoral head should be located in the medial lower quadrant of the intersection of these two lines. Shenton's line curves along the femoral metaphysis and connects smoothly to the inner margin of the pubis. In a child with hip subluxation or dislocation, this line consists of two separate arcs and is described as broken. The acetabular index is the angle between a line drawn along the margin of the acetabulum and Hilgenreiner's line; in normal newborns, it averages 27.5 degrees and decreases with age.

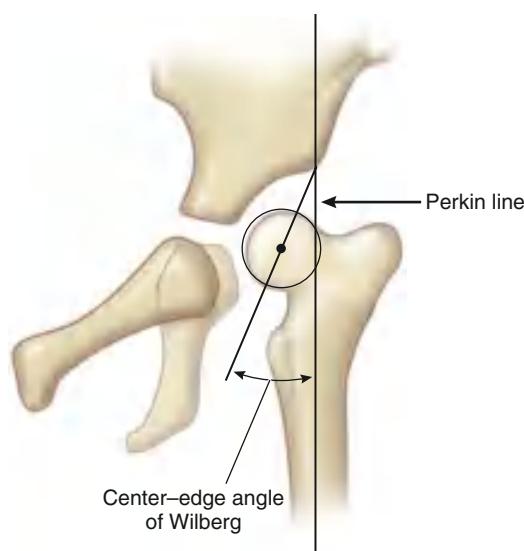


Fig. 719.9 Center-edge angle of Wilberg, which is the angle that is formed between the Perkin's line and a line drawn from the lateral lip of the acetabulum through the center of the femoral head. This angle, which is a useful measure of hip position in older children, is considered normal if it is more than 19 degrees in children between the ages of 6 and 13 years. It increases with age. (From Kim HK, Herring JA. Developmental dysplasia of the hip. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig. 13.31.)

The **acetabular index** is the angle formed between Hilgenreiner's line and a line drawn from the depth of the acetabular socket to the most lateral ossified margin of the roof of the acetabulum. This angle measures the development of the osseous roof of the acetabulum. In the newborn, the acetabular index can be up to 40 degrees; by 4 months in the normal infant, it should be no more than 30 degrees. In the older child, the **center-edge angle of Wilberg** is a useful measure of femoral head coverage. This angle is formed at the juncture of the Perkins line and a line connecting the lateral margin of the acetabulum to the center of the femoral head (Fig. 719.9). In children 6-13 years, an angle >19 degrees is normal, whereas in children 14 years and older, an angle >25 degrees is considered normal.

TREATMENT

The goals in the management of DDH are to obtain and maintain a concentric reduction of the femoral head within the acetabulum to provide the optimal environment for the normal development of both the femoral head and acetabulum. The later the diagnosis of DDH is made, the more difficult it is to achieve these goals, the less potential

there is for acetabular and proximal femoral remodeling, and the more complex the required treatments.

Newborns and Infants Younger Than 6 Months

Newborns' hips that are Barlow positive (reduced but dislocatable) or Ortolani positive (dislocated but reducible) should generally be treated with a Pavlik harness as soon as the diagnosis is made. The management of newborns with dysplasia who are younger than 4 weeks of age is less clear. A significant proportion of these hips normalize within 3-4 weeks; consequently, many physicians prefer to reexamine these newborns after a few weeks before making treatment decisions. A study of newborns with mildly dysplastic hips based on the results of an ultrasound (alpha angles between 43 and 50 degrees) and who were randomly assigned to receive immediate abduction splinting or active sonographic surveillance from birth with Frejka splinting (if treatment was subsequently needed) revealed no difference in radiologic findings at 6 years of age.

Triple diapers or abduction diapers have *no place* in the treatment of DDH in the newborn; they are usually ineffective and give the family a false sense of security. Acetabular dysplasia, subluxation, or dislocation can all be readily managed with the Pavlik harness. Although other braces are available (von Rosen splint, Ilfeld splint, Frejka pillow), the Pavlik harness remains the most commonly used device worldwide (Fig. 719.10). By maintaining the Ortolani-positive hip in a Pavlik harness on a full-time basis for 6 weeks, hip instability resolves in approximately 75% of cases. After 6 months of age, the failure rate for the Pavlik harness is >50% because it is difficult to maintain the increasingly active and crawling child in the harness. Frequent examinations and readjustments are necessary to ensure that the harness is correctly fitted. The anterior straps of the harness should be set to maintain the hips in flexion (usually ~90-100 degrees); excessive flexion is discouraged because of the risk of femoral nerve palsy. The posterior straps are designed to encourage abduction. These are generally set to allow adduction just to neutral, because forced abduction by the harness can lead to avascular necrosis of the femoral epiphysis.

If follow-up examinations and ultrasounds do not demonstrate concentric reduction of the hip after 3-4 weeks of Pavlik harness treatment, the harness should be abandoned. Continued use of the harness beyond this period in a persistently dislocated hip can cause **Pavlik harness disease** or wearing away of the posterior aspect of the acetabulum, which can make the ultimate reduction less stable.

Children 6 Months to 2 Years of Age

The principal goals in the treatment of late-diagnosed dysplasia are to obtain and maintain reduction of the hip without damaging the femoral head. Closed reductions are performed in the operating room under general anesthesia. The hip is moved to determine the range of motion (ROM) in which it remains reduced. This is



Fig. 719.10 Photograph of a Pavlik harness.

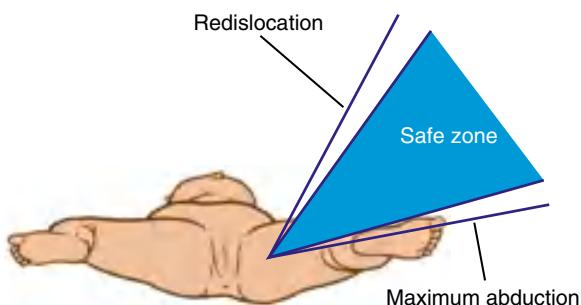


Fig. 719.11 Diagram of the safe zone of Ramsey.

compared to the maximal ROM to construct a “safe zone” (Fig. 719.11). An arthrogram obtained at the time of reduction is very helpful for evaluating the depth and stability of the reduction (Fig. 719.12). The reduction is maintained in a well-molded spica cast, with the “human position” of moderate flexion and abduction being the preferred position. After the procedure, single-cut CT or MRI may be used to confirm the reduction. Twelve weeks after closed reduction, the plaster cast is removed; an abduction orthosis is often used at this point to encourage further remodeling of the acetabulum. Failure to obtain a stable hip with a closed reduction indicates the need for an open reduction. In patients younger than 18 months of age, a concomitant acetabular or femoral procedure is rarely required. The potential for acetabular development after closed or open reduction is excellent and continues for 4–8 years after the procedure.

Children Older Than 2 Years

Children 2–6 years of age with a hip dislocation usually require an open reduction. In this age-group, a concomitant femoral shortening osteotomy is often performed to reduce the pressure on the proximal femur and minimize the risk of osteonecrosis. Because the potential for acetabular development is markedly diminished in these older children, a pelvic osteotomy is usually performed in conjunction with the open reduction. Postoperatively, patients are immobilized in a spica cast for 6–12 weeks.

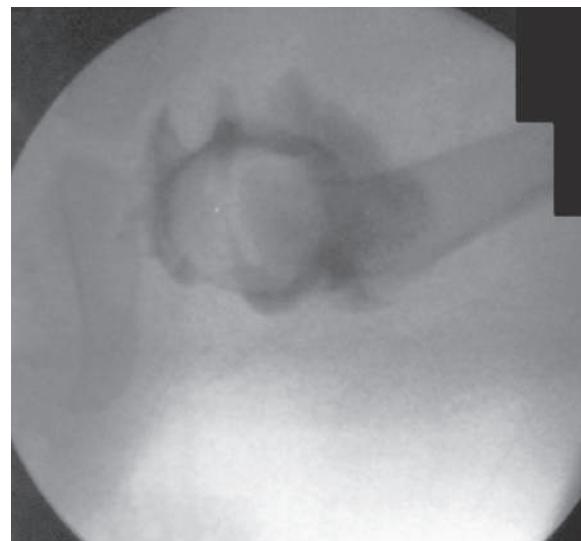


Fig. 719.12 Arthrogram of a reduced hip for evaluating the stability of reduction.

COMPLICATIONS

The most important complication of DDH is **avascular necrosis** of the femoral epiphysis. Reduction of the femoral head under pressure or in extreme abduction can result in occlusion of the epiphyseal vessels and produce either partial or total infarction of the epiphysis. Revascularization soon follows, but if the physis is severely damaged, abnormal growth and development can occur. Management, as previously outlined, is designed to minimize this complication. With appropriate treatment, the incidence of avascular necrosis for DDH is reduced to 5–15%. Other complications in DDH include redislocation, residual subluxation, acetabular dysplasia, pressure ulcers from prolonged casting, and postoperative complications, including wound infections.

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719.2 Transient Monoarticular Synovitis (Toxic Synovitis)

Wudbhav N. Sankar, Jennifer J. Winell, B. David Horn, and Lawrence Wells

Transient synovitis (toxic synovitis) is thought to be a reactive arthritis and is one of the most common causes of hip pain in young children.

ETIOLOGY

The cause of transient synovitis remains unknown. It has been variously described as a nonspecific inflammatory condition or as a post-viral immunologic synovitis because it tends to follow recent viral illnesses.

CLINICAL MANIFESTATIONS

Although transient synovitis can occur in all age-groups, it is most prevalent in children between 3 and 8 years of age, with a mean onset at age 6 years. Approximately 70% of all affected children have had a nonspecific upper respiratory tract infection the 7–14 days before symptom onset. Symptoms often develop acutely (~3 days) and usually consist of pain in the groin, anterior thigh, or knee, which may be referred from the hip. These children are usually able to bear weight on the affected limb and typically walk with an antalgic gait with the foot externally rotated. The hip is not held flexed, abducted, or laterally rotated unless a significant effusion is present. They are often afebrile or have a low-grade fever ($\leq 38^{\circ}\text{C}$).

DIAGNOSIS

Transient synovitis is a diagnosis of exclusion, and laboratory and radiographic tests can be useful to rule out other more serious conditions. In transient synovitis, infection laboratory tests (ESR: <20 mm/hr, serum CRP: normal or ≤ 2 mg/dL, and WBC: <12,000 cells/mm 3) are relatively normal, but on occasion a mild elevation in the ESR is observed. AP and Lauenstein (frog-leg) lateral radiographs of the pelvis may be acquired and are also usually found to be normal. Ultrasonography of the hip is the preferred imaging modality and often demonstrates a small joint effusion.

The most important condition to exclude before confirming a diagnosis of toxic synovitis is septic arthritis. Children with septic arthritis usually appear more systemically ill and have more pain than those with transient synovitis, often refusing to walk or move their hip at all. High fever, refusal to walk, and elevations of the ESR, serum CRP, and WBC all suggest a diagnosis of septic arthritis. If the clinical scenario is suspicious for septic arthritis, an ultrasound-guided aspiration of the hip joint should be performed to make the definitive diagnosis (see Chapter 726). An exception to these criteria is hip septic arthritis due to *Kinella kingae* or *Lyme disease*, which may have minimal inflammation and low-grade or no fever. Synovial fluid white blood cell counts are low in toxic synovitis (<25,000) and much higher in Lyme and septic arthritis (50,00–200,000). MRI may be needed to evaluate for an associated osteomyelitis if the patient has concerning examination or laboratory findings (see Chapter 725).

TREATMENT

The treatment of transient monoarticular synovitis of the hip is symptomatic. Recommended therapies include activity limitation and relief of weight bearing until the pain subsides. Antiinflammatory agents and analgesics can shorten the duration of pain. Most children improve in 5–7 days and recover completely within 3–6 weeks.

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719.3 Legg-Calvé-Perthes Disease

Wudbhav N. Sankar, Jennifer J. Winell, B. David Horn, and Lawrence Wells

Legg-Calvé-Perthes disease (LCPD) is a hip disorder of unknown etiology that results from temporary interruption of the blood supply to the proximal femoral epiphysis, leading to osteonecrosis and femoral head deformity.

ETIOLOGY

Although the underlying etiology remains obscure, most authors agree that the final common pathway in the development of LCPD is disruption of the vascular supply to the femoral epiphysis, which results in ischemia and osteonecrosis. Infection, trauma, and transient synovitis have all been proposed as causative factors but are unsubstantiated. Factors leading to thrombophilia, an increased tendency to develop thrombosis, and a reduced ability to lyse thrombi have been identified. Factor V Leiden mutation, deficiency of proteins C and S, lupus anticoagulant, anticardiolipin antibodies, antitrypsin, and plasminogen activator might play a role in the abnormal clotting mechanism. These abnormalities in the clotting cascade are thought to increase blood viscosity and the risk for venous thrombosis. Poor venous outflow leads to increased intraosseous pressure, which, in turn, impedes arterial inflow, causing ischemia and cell death. LCPD is rarely due to pathogenic variants in *COL2A1*, which is usually sporadic (*de novo*) and manifests as an autosomal dominant trait.

EPIDEMIOLOGY

The incidence of LCPD in the United States is 1 in 1,200 children, with males 4–5 times more likely to be affected than females. The peak incidence of the disease is between the ages of 4 and 8 years. Bilateral

involvement is seen in approximately 10% of the patients, but the hips are usually in different stages of collapse.

PATHOGENESIS

Early pathologic changes in the femoral head are the result of ischemia and necrosis; subsequent changes result from the repair process. The disease course may have four stages, although variations have been described. The **initial stage** of the disease, which lasts an average of 6 months, is characterized by synovitis, joint irritability, and early necrosis of the femoral head. Revascularization then leads to osteoclastic-mediated resorption of the necrotic segment. The necrotic bone is replaced by fibrovascular tissue rather than new bone, which compromises the structural integrity of the femoral epiphysis. The second stage is the **fragmentation stage**, which typically lasts 8 months. During this stage, the femoral epiphysis begins to collapse, usually laterally, and begins to extrude from the acetabulum. The **healing stage**, which lasts approximately 4 years, begins with new bone formation in the subchondral region. Reossification begins centrally and expands in all directions. The degree of femoral head deformity depends on the severity of collapse and the amount of remodeling that occurs. The final stage is the **residual stage**, which begins after the entire head has reossified. A mild amount of remodeling of the femoral head still occurs until the child reaches skeletal maturity. LCPD often damages the proximal femoral physis, leading to a short neck (coxa breva) and trochanteric overgrowth.

CLINICAL MANIFESTATIONS

The most common presenting symptom is a limp of varying duration. Pain, if present, is usually activity related and may be localized in the groin or referred to the anteromedial thigh or knee region. *Failure to recognize that thigh or knee pain in a child may be secondary to hip pathology can cause further delay in the diagnosis.* Less commonly, the onset of the disease may be much more acute and may be associated with a failure to ambulate.

Antalgic gait (a limp characterized by a shortening of gait phase on the injured side to alleviate weight-bearing pain) may be particularly prominent after strenuous activity at the end of the day. Hip motion, primarily internal rotation and abduction, is limited. Early in the course of the disease, the limited abduction is secondary to synovitis and muscle spasm in the adductor group; however, with time and the subsequent deformities that can develop, the limitation of abduction can become permanent. A mild hip flexion contracture of 10–20 degrees may be present. Atrophy of the muscles of the thigh, calf, or buttock from disuse secondary to pain may be evident. An apparent leg-length inequality may be caused by an adduction contracture or true shortening on the involved side from femoral head collapse.

DIAGNOSIS

Routine plain radiographs are the primary diagnostic tool for LCPD. AP and Lauenstein (frog-leg) lateral views are used to diagnose, stage, provide prognosis for, and follow the course of the disease (Fig. 719.13). It is important when evaluating disease progression that all radiographs be viewed sequentially and compared with previous radiographs to assess the stage of the disease and to determine the true extent of epiphyseal involvement.

In the initial stage of LCPD, the radiographic changes include a decreased size of the ossification center, lateralization of the femoral head with widening of the medial joint space, a subchondral fracture, and physeal irregularity. In the fragmentation stage, the epiphysis appears fragmented, and there are scattered areas of increased radiolucency and radiodensity. During the reossification stage, the bone density returns to normal via new (woven) bone formation. The residual stage is marked by the reossification of the femoral head, gradual remodeling of head shape until skeletal maturity, and remodeling of the acetabulum.

In addition to these radiographic changes, several classic radiographic signs have been reported that describe a “head at risk” for severe deformity. Lateral extrusion of the epiphysis, a horizontal physis, calcification lateral to the epiphysis, subluxation of the hip, and a

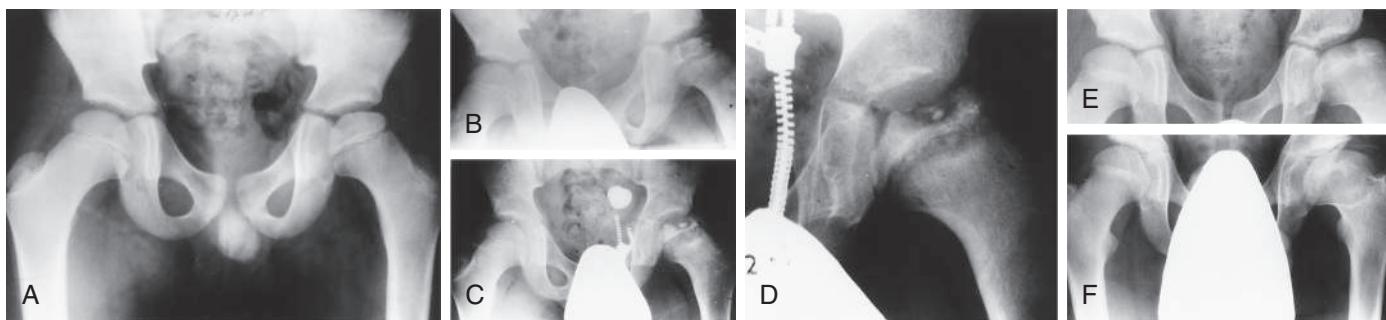


Fig. 719.13 Radiographic evolution of Legg-Calvé-Perthes disease, with onset in a male at 10-yr, 11-mo of age. Despite the late age of onset, the femoral head remodels well as the patient approaches skeletal maturity. **A**, Anteroposterior (AP) radiograph obtained at onset of the disorder shows increased density in the femoral head and apparent widening of the joint space (Waldenström's initial stage). **B**, AP radiograph obtained 9 mo after onset shows the head entering the fragmentation stage. The central fragment remains dense and has collapsed relative to the lateral portion (lateral pillar) of the femoral head. The lateral pillar is lucent but has not collapsed, and the hip is classified as group B in the lateral pillar classification system. The joint space has widened further. **C**, AP radiograph obtained 17 mo after onset shows early reossification of the femoral head (the healing stage). **D**, A closer view of the femoral head at 22 mo after onset of disease. There is still widening of the joint space, and the acetabulum has a bicompartamental appearance. **E**, AP radiograph obtained 4 yr after onset. The femoral head is healed and in the residual state. There is still widening of the joint space and incongruity of the head with the acetabulum. **F**, AP radiograph obtained 6 yr after onset shows improved roundness of the femoral head and better joint congruity. (From Kim HK, Herring JA. Legg-Calvé-Perthes disease. In: Herring JA, ed. *Tachdjian's Pediatric Orthopaedics*, 6th ed. Philadelphia: Elsevier; 2022: Fig. 14.19.)

radiolucent horizontal V in the lateral aspect of the physis (Gage's sign) are all associated with a poor prognosis.

In the absence of changes on plain radiographs, particularly in the early stages of the disease, MRI is useful to diagnose early infarction and determine the degree of impaired perfusion. It is being used more in early stages to help determine prognosis. During the remodeling or residual stages, MRI is extremely helpful to define the abnormal anatomy and determine the extent of intraarticular injury. Arthrography can be useful to dynamically assess the shape of the femoral head, demonstrate whether a hip can be contained, and diagnose hinge abduction. **Table 719.1** outlines the differential diagnosis.

CLASSIFICATION

A four-group classification is based on the amount of femoral epiphysis involvement and a set of radiographic "head at-risk" signs. **Group I** hips have anterior femoral head involvement of 25%, no sequestrum (an island of dead bone within the epiphysis), and no metaphyseal abnormalities. **Group II** hips have up to 50% involvement and a clear demarcation between involved and uninvolving segments. Metaphyseal cysts may be present. **Group III** hips display up to 75% involvement and a large sequestrum. In **group IV**, the entire femoral head is involved. Use of this classification system has been limited because of a high degree of interobserver variability.

The **Herring lateral pillar classification** is the most widely used radiographic classification system for determining treatment and prognosis during the active stage of the disease (Fig. 719.14). The Herring classification has a high degree of interobserver reliability. Classification is based on several radiographs taken during the early fragmentation stage. The lateral pillar classification system for LCPD evaluates the shape of the femoral head epiphysis on AP radiograph of the hip. The head is divided into three sections or pillars. The lateral pillar occupies the lateral 15–30% of the head width, the central pillar is approximately 50% of the head width, and the medial pillar is 20–35% of the head width. The degree of involvement of the lateral pillar can be subdivided into three groups. In **group A**, the lateral pillar is radiographically normal. In **group B**, the lateral pillar has some lucency, but >50% of the lateral pillar height is maintained. In **group C**, the lateral pillar is more lucent than in group B, and <50% of the pillar height remains. Herring has

Table 719.1 Differential Diagnosis of Legg-Calvé-Perthes Disease

OTHER CAUSES OF AVASCULAR NECROSIS

- Sickle cell disease
- Other hemoglobinopathies (e.g., thalassemia)
- Chronic myelogenous leukemia
- Steroid medication
- Sequelae of traumatic hip dislocation
- Treatment of developmental dysplasia of the hip
- Septic arthritis
- Systemic lupus erythematosus (SLE)

SKELETAL DYSPLASIAS MIMICKING PERTHES

- Multiple epiphyseal dysplasia
- Spondyloepiphyseal dysplasia
- Mucopolysaccharidoses
- Hypothyroidism

OTHER SYNDROMES

- Osteochondromatosis
- Metachondromatosis
- Schwartz-Jampel syndrome
- Trichorhinophalangeal syndrome
- Maroteaux-Lamy syndrome
- Martsolf syndrome
- Stickler syndrome

From Kim HKW, Herring JA. Legg-Calvé-Perthes disease. In: Herring JA, ed. *Tachdjian's Pediatric Orthopaedics*, 6th ed. Philadelphia: Elsevier; 2022: Box 14.6, p. 561.

added a B/C border group to the classification system to describe patients with approximately 50% collapse of the lateral pillar.

NATURAL HISTORY AND PROGNOSIS

Children who develop signs and symptoms of LCPD before the age of 6 years tend to recover with fewer residual problems. Patients older than 9 years of age at presentation usually have a poor prognosis. The reason for this difference is that the remodeling potential of the femoral head is higher in younger children. Greater extent of femoral head involvement and duration of the disease process are additional factors associated with a poor prognosis. Hips classified as Catterall groups III and IV and lateral pillar group C generally have a poor prognosis.

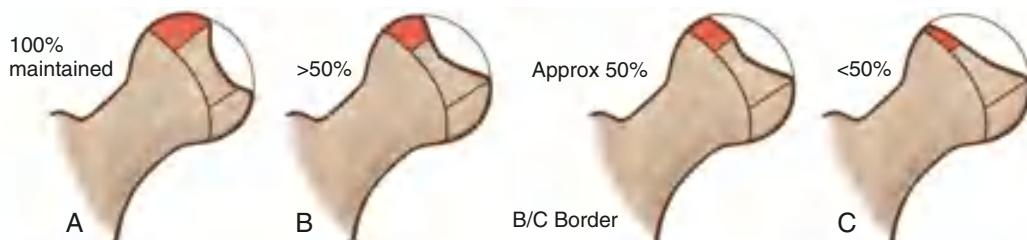


Fig. 719.14 Lateral pillar classification for Legg-Calvé-Perthes disease. A, There is no involvement of the lateral pillar. B, More than 50% of the lateral pillar height is maintained. B/C Border, Lateral pillar is narrowed or poorly ossified with approximately 50% height maintained. C, Less than 50% of the lateral pillar height is maintained.

TREATMENT

The goal of treatment in LCPD is preservation of a spherical, well-covered femoral head and maintenance of hip ROM that is close to normal. Although the treatment of LCPD remains controversial, most authors agree that the general approach to these patients should be guided by the principle of containment. This principle is predicated on the fact that while the femoral head is fragmenting, and therefore in a softened condition, it is best to contain it entirely within the acetabulum; by doing so, the acetabulum acts as a mold for the regenerating femoral head. Conversely, failure to contain the head permits it to deform, with resulting extrusion and impingement on the lateral edge of the acetabulum. To be successful, containment must be instituted early while the femoral head is still moldable; once the head has healed, repositioning the femoral epiphysis will not aid remodeling and can, in fact, worsen symptoms.

Initial options to manage symptoms include activity limitation, protected weight bearing, and nonsteroidal antiinflammatory medications. Nonoperative containment can be achieved by using a Petrie cast to restore abduction and to direct the femoral head deeper into the acetabulum. Petrie casts are two long-leg casts that are connected by a bar and can be helpful to keep the hips in abduction and internal rotation (the best position for containment). Casting is generally done in conjunction with an arthrogram to confirm containment and a tenotomy of the adductor tendons. After 6 weeks, patients can be transitioned into an abduction orthosis with limited weight bearing. Several older studies did not support the efficacy of casting and long-term bracing as a means of containment, but a subsequent large series reported excellent results with this form of treatment.

Surgical containment may be approached from the femoral side, the acetabular side, or both sides of the hip joint. A varus osteotomy of the proximal femur is the most common procedure. Pelvic osteotomies in LCPD are divided into three categories: acetabular rotational osteotomies, shelf procedures, and medial displacement or Chiari osteotomies. Any of these procedures can be combined with a proximal femoral varus osteotomy when severe deformity of the femoral head cannot be contained by a pelvic osteotomy alone.

After healing of the epiphysis, surgical treatment shifts from containment to management of the residual deformity. Patients with hinge abduction or joint incongruity might benefit from a valgus-producing proximal femoral osteotomy. Coxa breva and overgrowth of the greater trochanter can be managed by performing an advancement of the trochanter. This helps restore the length-tension relationship of the abductor mechanism and can alleviate abductor fatigue. Patients with femoroacetabular impingement from irregularity of the femoral head often can be helped with an osteoplasty or cheilectomy of the offending prominence.

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719.4 Slipped Capital Femoral Epiphysis

Wudbhav N. Sankar, Jennifer J. Winell, B. David Horn, and Lawrence Wells

Slipped capital femoral epiphysis (SCFE) is a hip disorder that affects adolescents, most often between 10–16 years of age, and involves failure of the physis and displacement of the femoral head relative to the neck.

CLASSIFICATION

SCFEs may be classified temporally, according to onset of symptoms (acute, chronic, acute-on-chronic); functionally, according to the patient's ability to bear weight (stable or unstable); or morphologically, as the extent of displacement of the femoral epiphysis relative to the neck (mild, moderate, or severe), as estimated by measurement on radiographic or CT images.

An **acute** SCFE is characterized as one occurring in a patient who has prodromal symptoms for ≤ 3 weeks and should be distinguished from a purely traumatic separation of the epiphysis in a previously normal hip (a true Salter-Harris type I fracture; see Chapter 724). The patient with an acute slip usually has some prodromal pain in the groin, thigh, or knee, and usually reports a relatively minor injury (a twist or fall) that is not sufficiently violent to produce an acute fracture of this severity.

Chronic SCFE is the most common form of presentation. Typically, an adolescent presents with a few months' history of vague groin, thigh, or knee pain and a limp. Radiographs show a variable amount of posterior and inferior migration of the femoral epiphysis and remodeling of the femoral neck in the same direction.

Children with **acute-on-chronic** SCFE can have features of both acute and chronic conditions. Prodromal symptoms have been present for >3 weeks with a sudden exacerbation of pain. Radiographs demonstrate femoral neck remodeling and further displacement of the capital epiphysis beyond the remodeled point of the femoral neck.

The stability classification separates patients based on their ability to ambulate and is more useful in predicting prognosis and establishing a treatment plan. The SCFE is considered *stable* when the child is able to walk with or without crutches. A child with an *unstable* SCFE is unable to walk with or without walking aids. Patients with unstable SCFE have a much higher prevalence of osteonecrosis (up to 50%) compared to those with stable SCFE (nearly 0%). This is most likely because of the vascular injury caused at the time of initial displacement.

SCFE may also be categorized by the degree of displacement of the epiphysis on the femoral neck. The head-shaft angle difference is <30 degrees in mild slips, between 30 and 60 degrees in moderate slips, and >60 degrees in severe slips, compared to the normal contralateral side.

SCFE is one of many etiologies of acquired **coxa vara** defined by an abnormal decrease in the femoral neck shaft angle (Table 719.2).

Table 719.2 Classification of Coxa Varus**ACQUIRED COXA VARA**

- Slipped capital femoral epiphysis
- Sequelae of avascular necrosis of the femoral epiphysis
- Legg-Calvé-Perthes disease
- Traumatic coxa vara
- Femoral neck fracture
- Traumatic hip dislocation
- Sequelae of reduction for developmental dysplasia of the hip
- Septic necrosis
- Other causes of avascular necrosis of the immature femoral head
- Coxa vara associated with pathologic bone disorders
- Osteogenesis imperfecta
- Fibrous dysplasia
- Renal osteodystrophy
- Osteopetrosis
- Other bone-softening conditions affecting the femoral neck
- Congenital femoral deficiency with coxa vara

DEVELOPMENTAL COXA VARA

- Isolated (may be bilateral)
- Associated with a skeletal dysplasia

 - Cleidocranial dysostosis
 - Metaphyseal dysostosis
 - Other skeletal dysplasias

From Sucato DJ. Congenital coxa vara. In: Herring JA, ed. *Tachdjian's Pediatric Orthopaedics*, 6th ed. Philadelphia: Elsevier; 2022: Box 16.1, p. 617.

ETIOLOGY AND PATHOGENESIS

SCFEs are most likely caused by a combination of mechanical and endocrine factors. The plane of cleavage in most SCFEs occurs through the hypertrophic zone of the physis. During normal puberty, the physis becomes more vertically oriented, which converts mechanical forces from compression to shear. In addition, the hypertrophic zone becomes elongated in pubertal adolescents due to high levels of circulating hormones. This widening of the physis decreases the threshold for mechanical failure. Normal ossification depends on a number of different factors, including the thyroid hormone, vitamin D, and calcium. Consequently, it is not surprising that SCFEs occur with increased incidence in children with medical disorders, such as hypothyroidism, hypopituitarism, and renal osteodystrophy. Obesity, one of the largest risk factors for SCFE, affects both the mechanical load on the physis and the level of circulating hormones. The combination of mechanical and endocrine factors results in gradual failure of the physis, which allows posterior and inferior displacement of the head in relation to the femoral neck.

EPIDEMIOLOGY

The annual incidence of SCFE is 2 per 100,000 in the general population. Obesity is the most closely associated risk factor in the development of SCFE; approximately 65% of the patients are in the >90th percentile in weight-for-age profiles. There is a predilection for males to be affected more often than females and for the left hip to be affected more often than the right. Bilateral involvement has been reported in as many as 60% of cases, nearly half of which may be present at the time of initial presentation.

CLINICAL MANIFESTATIONS

The classic patient presenting with a SCFE is an obese male between the ages of 11 and 16 years. Females present earlier, usually between 10 and 14 years of age. Patients with chronic and stable SCFEs tend to present after weeks to months of symptoms. Patients usually limp to some degree and have an externally rotated lower extremity. Physical examination of the affected hip reveals a restriction of internal rotation, abduction, and flexion. Commonly, the examiner notes that as the affected hip is flexed, the thigh tends to rotate progressively into more external rotation with increased flexion (Fig. 719.15). Most patients complain of groin symptoms, but isolated



Fig. 719.15 Clinical examination of a patient with a stable slipped capital femoral epiphysis. Hip flexion and external rotation are limited. With flexion of the affected hip, the limb rotates externally. (From Podoleczwa D. Slipped capital femoral epiphysis. In: Herring JA, ed. *Tachdjian's Pediatric Orthopaedics*, 6th ed. Philadelphia: Elsevier; 2022: Fig. 15.5.)

thigh or knee pain is a common presentation from referred pain along the course of the obturator nerve. Missed or delayed diagnosis often occurs in children who present with knee pain and do not receive appropriate imaging of the hip. Patients with unstable SCFEs usually present in an urgent fashion. Children typically refuse to allow any ROM of the hip; much like a hip fracture, the extremity is shortened, abducted, and externally rotated.

DIAGNOSTIC STUDIES

AP and frog-leg lateral radiographic views of both hips are usually the only imaging studies needed to make the diagnosis. Because approximately 25% of patients have a contralateral slip on initial presentation, it is critical that both hips be carefully evaluated by the treating physician. Radiographic findings include widening and irregularity of the physis, a decrease in epiphyseal height in the center of the acetabulum, a crescent-shaped area of increased density in the proximal portion of the femoral neck, and the "blanch sign of Steel" corresponding to the double density created from the anteriorly displaced femoral neck overlying the femoral head. In an unaffected patient, Klein's line, a straight line drawn along the superior cortex of the femoral neck on the AP radiograph, should intersect some portion of the lateral capital femoral epiphysis. With progressive displacement of the epiphysis, Klein's line no longer intersects the epiphysis (Fig. 719.16). Although some of these radiographic findings can be subtle, most diagnoses can be readily made on the frog-leg lateral view, which reveals the characteristic posterior and inferior displacement of the epiphysis in relation to the femoral neck (Fig. 719.17).

TREATMENT

Once the diagnosis is made, the patient should be admitted to the hospital immediately and placed on bed rest. Allowing the child to go home without definitive treatment increases the risk that a stable SCFE will become an unstable SCFE and that further displacement will occur. Children with atypical presentations (younger than 10 years of age, thin body habitus) should have screening labs sent to rule out an underlying endocrinopathy.

The goal of treatment is to prevent further progression of the slip and to stabilize (i.e., close) the physis. Although various forms of treatment have been used in the past, including spica casting, the current gold standard for the treatment of SCFE is *in situ* pinning with a single large screw (Fig. 719.18). The term *in situ* implies that no attempt is made to reduce the displacement between the epiphysis and femoral neck because doing so increases the risk of

osteonecrosis. Screws are typically placed percutaneously under fluoroscopic guidance. Postoperatively, most patients are allowed partial weight bearing with crutches for 4–6 weeks, followed by a gradual return to normal activities. Patients should be monitored with serial radiographs to be sure that the physis is closing and that the slip is stable. After healing from the initial stabilization, patients with severe residual deformity may be candidates for proximal femoral osteotomy to correct the deformity, reduce impingement, and improve range of motion.

Because 20–40% of children will develop a contralateral SCFE at some point, many orthopedists advocate prophylactic pin fixation of the contralateral (normal) side in patients with a unilateral SCFE. The benefits of preventing a possible slip must be balanced with the risks of performing a potentially unnecessary surgery. Several recent studies have attempted to analyze decision models for prophylactic pinning, but controversy remains regarding the optimal course of treatment. If

prophylactic pinning is not performed, patients and their families must be instructed to return immediately if they develop contralateral hip or leg pain.

COMPLICATIONS

Osteonecrosis and chondrolysis are the two most serious complications of SCFE. Osteonecrosis, or avascular necrosis, usually occurs as a result of injury to the retinacular vessels. This can be caused by an initial force of injury, particularly in unstable slips, forced manipulation of an acute or unstable SCFE, compression from intracapsular hematoma, or as a direct injury during surgery. Partial forms of osteonecrosis can also appear after internal fixation; this can be caused by a disruption of the intraepiphyseal blood vessels. Chondrolysis, on the other hand, is an acute dissolution of articular cartilage in the hip. There are no clear causes of this complication, but it is thought to be associated with more severe slips, to occur more commonly in females, and to be associated with pins or screws protruding out of the femoral head.

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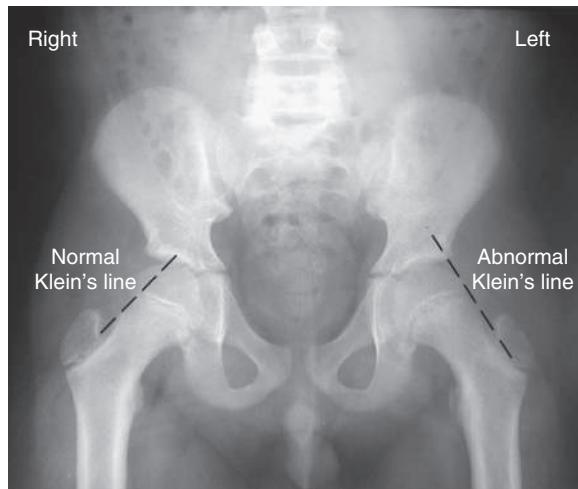


Fig. 719.16 Illustration of Klein's line.

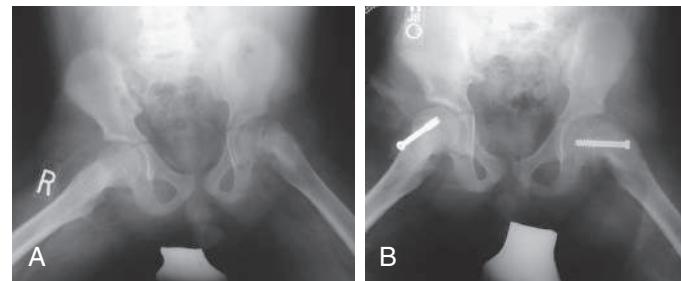


Fig. 719.18 Preoperative (A) and postoperative (B) radiographs demonstrating the in situ pinning in a case of slipped capital femoral epiphysis.

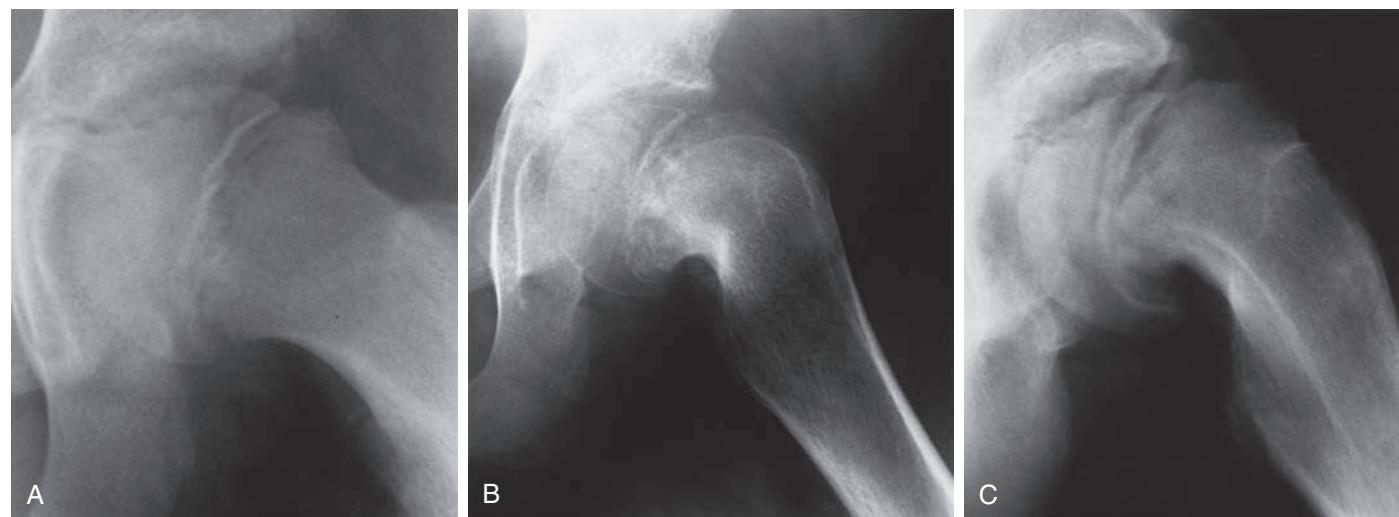


Fig. 719.17 Radiographic appearance of slipped capital femoral epiphysis (SCFE) on presentation. A, Appearance of acute SCFE on a frog-leg lateral view. The displacement of the epiphysis is suggestive of a Salter-Harris type I fracture of the upper femoral physis. There are no secondary adaptive changes noted in the femoral neck. B, Frog-leg lateral radiographs in a patient with many months of thigh discomfort and a chronic slipped epiphysis. Adaptive changes in the femoral neck predominate, and the epiphysis is centered on the adapted femoral neck. C, Frog-leg lateral radiographs of a patient with acute-on-chronic SCFE. The patient had several months of vague thigh pain, with sudden, severe exacerbation of that pain. The acute displacement of the epiphysis is evident. Unlike in acute SCFE (see A), secondary adaptive remodeling changes are also present in the femoral neck, beyond which the epiphysis has acutely displaced. (From Podeszwa D. Slipped capital femoral epiphysis. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig. 15.1, p. 583.)

Chapter 720

The Spine

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Abnormalities of the spine can result from a variety of causes, including congenital, developmental, and traumatic. In addition to spinal deformities, back pain is also prevalent in children and adolescents and may be caused by a number of serious or relatively benign pathologies.

NORMAL SPINAL CURVATURES

A normal spinal column is straight in the anteroposterior (AP, coronal) plane but has curvatures in the lateral (sagittal) plane. Normal cervical lordosis, thoracic kyphosis, and lumbar lordosis regions are biomechanically advantageous as they maintain relationships of the body relative to the forces of gravity, which is important for balance. These curvatures also help to conserve energy by minimizing the amount of muscular activity required to maintain an upright posture.

Abnormalities affecting these normal curvatures, termed *sagittal plane imbalances*, can be measured on a lateral spine radiograph. A vertical line, or *plumb line*, drawn from the center of the seventh cervical vertebra should normally fall through the posterosuperior corner of the sacrum. Disorders affecting sagittal alignment include thoracic hyperkyphosis and lumbar hyperlordosis. In contrast, although scoliosis is *actually* a three-dimensional deformity not limited to a single anatomic plane, it is most commonly *described* as a frontal or coronal plane deformity with curvatures away from the midline in this plane.

OVERVIEW OF ABNORMAL SPINAL CURVATURES

The most common spinal deformities are scoliosis and kyphosis. Early diagnosis is important, as a subset of patients may be candidates for early interventions to prevent curve progression. Bracing has been proven to reduce the number of patients with curve progressing to require surgery in **adolescent idiopathic scoliosis (AIS)**.

Scoliosis may be idiopathic, due to congenital bony deformities, or may be associated with a variety of underlying conditions, including neuromuscular diseases, connective tissue diseases, or genetic syndromes. Oftentimes, the pediatrician is the first to diagnose these conditions.

Although parents and families are often most concerned about potential cosmetic abnormalities, the physician diagnosing a patient with a spinal deformity must carefully consider both the potential for underlying causes requiring treatment and the patient's long-term prognosis. Progressive curvatures in the neuromuscular population may result in respiratory insufficiency in addition to a loss of sitting balance. Other conditions such as neurofibromatosis are associated with a specific dystrophic curve pattern that can rapidly progress. Sometimes, a spinal deformity might be the first sign of an underlying syndrome. Parents and the patient need an understanding of the deformity, how it may progress, and potential complications associated with the diagnosis. A classification of common spinal abnormalities is presented in [Table 720.1](#).

720.1 Idiopathic Scoliosis

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Scoliosis is a complex, three-dimensional spinal deformity, defined in the coronal plane as a curve of at least 10 degrees on a posteroanterior (PA) radiograph of the spine. Affected vertebrae are axially rotated,

causing a visible prominence to be noted on the **Adams forward bend test**. The sagittal plane is also affected, leading to abnormalities such as decreased thoracic kyphosis.

ETIOLOGY

By definition, the etiology of idiopathic scoliosis remains unknown despite a considerable body of research. It is likely that the disease is multifactorial, with genetic, hormonal, cellular, and anatomic contributions.

A genetic link has been proposed with sex-linked dominant, autosomal dominant, and polygenic inheritance patterns all suggested. Genetic involvement has been substantiated in studies of twins, demonstrating a 73% concordance rate for AIS in monozygotic twins compared to a 36% concordance rate in dizygotic twins.

AIS is 2 to 10 times more common in females than males. Investigators have attempted to explain this difference as a genetic effect: it has been hypothesized that males are not as susceptible to the involved genes as females. Therefore, affected males must inherit a larger number of susceptibility genes to have a scoliosis phenotype. Males would pass more susceptibility genes onto their children and would therefore have more affected children. Fathers with AIS transmit the gene to 80% of their children, but mothers with AIS transmit it to only 56% of their children.

Exome sequencing has identified pathogenic variants in the *COL11A2* collagen gene in 32% of AIS cases. *COMP* promotor methylation has been correlated with a younger age and larger main curve magnitude. Other gene variants have been found to demonstrate an association with AIS, including *PAX1*, *POC5*, the *Bsml* polymorphism in the vitamin D receptor gene, and *FBNI*. Additionally, females who have first-degree relatives with AIS have been found to have more severe curves and longer arm spans than females who have a spontaneous case.

Cellular structures may be involved in the disease process. Calmodulin, a regulator of the contractile properties of muscle, occurs at increased levels in the platelets of patients with progressive AIS. On a more cellular level, differences in the mRNA expression of *H19* and *ADIPOQ* have been described in the paraspinal musculature from the concave to the convex side of a curvature. Other functional evaluations of patients with AIS have noted abnormalities in proprioception and postural balance.

MRI studies of the brain in patients with AIS versus controls have found that the cerebellum of affected patients is hypertrophied in areas involving the somatosensory tracts, motor control, and response to visual stimulation. These areas of hypertrophy may be a compensation for impaired balance resulting from malalignment of the spine.

Approximately 30% of females with AIS have osteopenia on DEXA studies, and of these, 80% will have lifelong osteopenia. Osteopenia has been linked to an increased risk of curve progression. Insufficient vitamin D levels have been reported in over 90% of patients with operative AIS.

EPIDEMIOLOGY

Idiopathic scoliosis is the most common type of spinal curvature; 80% of cases are idiopathic. The overall prevalence of idiopathic scoliosis in skeletally immature patients ranges from 1–3% of the population. Most curves are mild and do not require treatment, with only 0.5% being >20 degrees and 0.3% exceeding 30 degrees. Curves of ≤10 degrees occur equally between males and females; however, those requiring an intervention occur in a 7:1 female-to-male ratio.

CLASSIFICATION OF IDIOPATHIC SCOLIOSIS

Idiopathic scoliosis is classified according to the age at onset. Patients with curves that are present before age 8–10 years have **early-onset scoliosis (EOS)**. Although EOS can have several etiologies, young patients without a clearly identified cause are classified as having idiopathic EOS. The subgroup of *infantile idiopathic EOS* refers to patients diagnosed before age 3 years and accounts for only 0.5–4% of cases of AIS. AIS affects patients 10 years of age and older and comprises 70–80% of all cases of idiopathic scoliosis.

Table 720.1 Classification of Spinal Deformities

SCOLIOSIS
<i>Idiopathic</i>
Infantile
Juvenile
Adolescent
<i>Congenital</i>
Failure of formation
Wedge vertebrae
Hemivertebrae
Failure of segmentation
Unilateral bar
Block vertebra
Mixed
Neuromuscular
Neuropathic diseases
Upper motor neuron
Cerebral palsy
Spinocerebellar degeneration (Friedreich ataxia, Charcot-Marie-Tooth disease)
Syringomyelia
Spinal cord tumor
Spinal cord trauma
Lower motor neuron
Poliomyelitis
Spinal muscular atrophy
Myopathies
Duchenne muscular dystrophy
Arthrogryposis
Other muscular dystrophies
Syndromes
Neurofibromatosis
Marfan syndrome
Compensatory
Leg-length discrepancy
KYPHOSIS
Postural kyphosis (flexible)
Scheuermann disease
Congenital kyphosis
Failure of formation
Failure of segmentation
Mixed

Adapted from the Terminology Committee, Scoliosis Research Society. A glossary of scoliosis terms. *Spine*. 1976;1:57.

CLINICAL PRESENTATION OF IDIOPATHIC SCOLIOSIS

When evaluating a patient with a structural spinal curvature, a thorough history and physical examination are required because idiopathic scoliosis is a diagnosis of exclusion. All other potential causes, including congenital bone malformations, neuromuscular and syndromic diseases, and tumors must systematically be excluded.

The curvature is frequently found on a positive screening by primary care physicians, through a school screening program, or because patients (or their family or friends) have noticed a cosmetic deformity. Citing the need for early identification of scoliosis to reduce the risk of operative complications with correction of large, neglected curves, the Scoliosis Research Society advocates for school screening. The BRAINST study, which definitively demonstrated that patients treated with Boston braces for 18 hours a day have a significantly lower incidence of curves progressing to the surgical range, supports the potential value of early detection through screening programs. Although the United States Preventive Services Task Force previously recommended against school screening programs, their updated 2018 recommendation statement concluded that evidence was insufficient to recommend for or against screening.

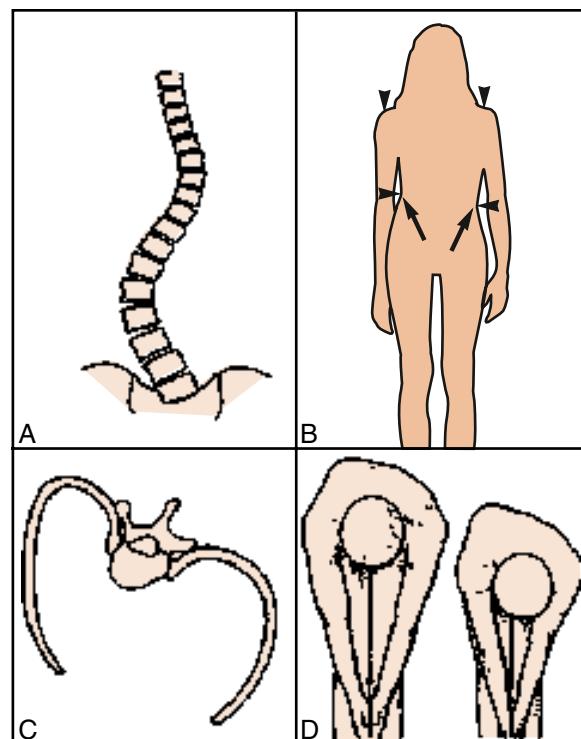


Fig. 720.1 Structural changes in idiopathic scoliosis. A, As curvature increases, alterations in body configuration develop in both the primary and compensatory curve regions. B, Asymmetry of shoulder height, waistline, and elbow-to-flank distance are common findings. C, Vertebral rotation and associated posterior displacement of the ribs on the convex side of the curve are responsible for the characteristic deformity of the chest wall (rib hump) in scoliosis patients. D, In the school screening examination for scoliosis, the patient bends forward at the waist. Rib asymmetry of even a small degree is obvious. (From Scoles PV. Spinal deformity in childhood and adolescence. In: Behrman RE, Vaughn VC III, eds. Nelson Textbook of Pediatrics, update 5. Philadelphia: WB Saunders; 1989.)

Back pain is not commonly a primary presenting complaint of patients with scoliosis, though when questioned, at least 30% of adolescents with idiopathic scoliosis will report some degree of back discomfort at some point in time. To keep this finding in perspective, a similar number of healthy adolescents complain of episodes of low back pain and discomfort. If a child presents with back pain associated with a curvature, it is important to do a careful history and physical exam, check spine radiographs, and rule out any diagnostic red flags (see Chapter 720.5). Look for other causes of pain in these patients, including spondylosis, spondylolisthesis, tethered cord, syrinx, herniated disk, or tumor such as osteoid osteoma or spinal cord tumor.

PHYSICAL EXAMINATION OF IDIOPATHIC SCOLIOSIS

Evaluate the patient in the standing position, from both the front and the side, to identify any asymmetry in the chest wall, trunk, or shoulders.

Begin the examination focusing on the back. The earliest abnormality noted on physical exam in patients with scoliosis is asymmetry of the posterior chest wall on forward bending. This test, called the Adams forward-bending test (Fig. 720.1), is performed by observing the patient's back while he or she is bending 45 degrees forward. This test can also be augmented with a scoliometer placed at the apex of the deformity. An inclination measuring 7 degrees or more has been suggested as the cutoff for orthopedic referral. Scoliosis is a three-dimensional deformity; patients develop a posterior rib hump on the convex side of the spinal curve as a result of the rotational component of the deformity. The anterior chest wall may be prominent on the

concavity of the curve due to outward rib rotation. Other associated findings may include shoulder imbalance, a lateral shift of the trunk, or an apparent leg-length discrepancy due to pelvic obliquity. A primary **limb length discrepancy** may also present as a lumbar spinal deformity. This lumbar curvature is compensatory and flexible, with the apex toward the shorter leg.

Next, examine the patient from the side to evaluate the degree of kyphosis and lordosis. The upper thoracic spine normally has a smooth, gently rounded kyphotic curve with an apex in the midthoracic region. The cervical spine and lower lumbar spine have concave, or lordotic curves. The magnitude of these sagittal contours varies with age. Children have less cervical lordosis and more lumbar lordosis than do adults or adolescents. When examining a patient with idiopathic scoliosis, a common finding is a loss of the normal thoracic kyphosis, resulting in what is called a relative thoracic lordosis or hypokyphosis.

Another common, benign finding in normal adolescent thoracic spines not associated with scoliosis is a flexible round back, or postural kyphosis. This can be corrected voluntarily when the patient extends his or her spine. This is different from sharp, abrupt, or accentuated forward angulation in the thoracic or thoracolumbar region, which is indicative of a pathologic kyphotic deformity.

The final exam component is a careful neurologic examination because scoliosis may be associated with an underlying neurologic diagnosis. Check superficial abdominal reflexes, extremity deep tendon reflexes, muscle strength, and atrophy and examine for clonus. Also, remember to examine the patient's feet because a cavovarus foot can be associated with a tethered cord. A high suspicion is necessary in patients with infantile and juvenile idiopathic scoliosis because up to 25% have an associated intraspinal abnormality such as a tethered spinal cord or syringomyelia. The index of suspicion for neurologic involvement is further raised in the presence of back pain or neurologic symptoms, bowel or bladder symptoms, café-au-lait spots, a sacral dimple, midline cutaneous abnormalities such as a hair patch or skin tag, unilateral foot deformity, or an atypical curve pattern.

RADIOGRAPHIC EVALUATION OF IDIOPATHIC SCOLIOSIS

Standing, high-quality PA and lateral radiographs of the *entire* spine are recommended at the initial evaluation for patients with clinical findings suggestive of a spinal deformity. Many children's hospitals have low-dose stereoradiographic imaging systems rather than conventional radiographs, which can minimize radiation exposure and also provide three-dimensional reconstructions of spinal deformity. On the PA radiograph, the degree of curvature is determined by the **Cobb angle**, in which the angle between the superior and inferior vertebrae most tilted into the curve is measured (Fig. 720.2).

Although the indications for performing an MRI are variable, it is helpful when an *underlying* cause for scoliosis such as a spinal cord abnormality is being considered. Patients with early-onset scoliosis have a higher incidence of associated cord anomalies. Other considerations include abnormal findings on the history or physical examination and atypical radiographic features, including abnormal curve patterns. Atypical radiographic findings include curve patterns such as a left thoracic curve, double thoracic curves, or high thoracic curves. Other radiographic abnormalities include widening of the spinal canal and erosive or dysplastic changes in the vertebral body or ribs. On the lateral radiograph, an increase in thoracic kyphosis or an absence of segmental lordosis may be suggestive of an underlying neurologic abnormality.

NATURAL HISTORY OF IDIOPATHIC SCOLIOSIS

Treatment decisions are based on the natural history of idiopathic scoliosis. Infantile idiopathic early-onset scoliosis may spontaneously resolve in 20–90% of cases. Patients with infantile scoliosis who have cognitive disabilities, curves presenting after 1 year of age, and larger magnitude curves are more likely to progress. A radiographic parameter called the Mehta angle can also be used to predict curve progression in infantile scoliosis. This measurement examines the vertebra at the apex of the thoracic curve. It measures the angle formed by a line

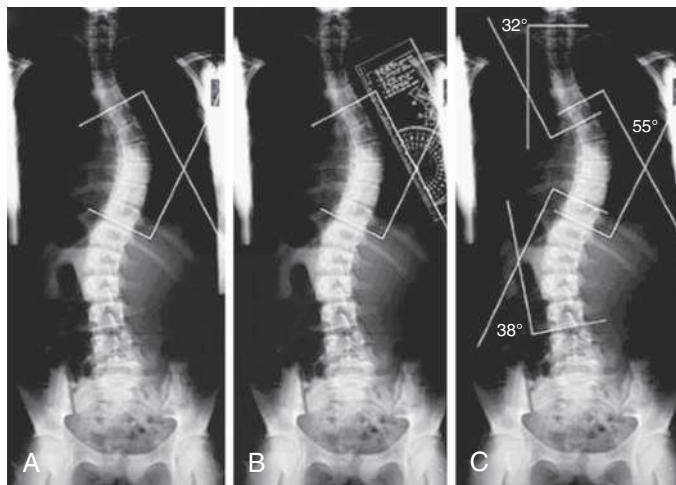


Fig. 720.2 A-C, Cobb angles measurements. (From Morrissey RT, Weinstein SL, eds. Lovell and Winter's Pediatric Orthopaedics, 3rd ed. Philadelphia: Lippincott Williams & Wilkins; 1990.)

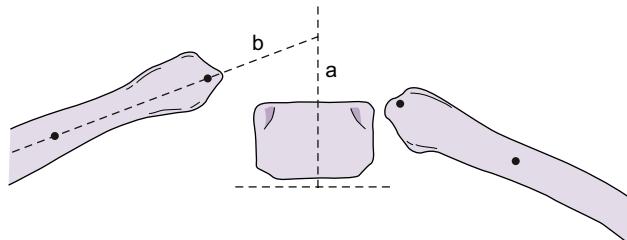


Fig. 720.3 Measuring the rib-vertebra angle difference (RVAD). A line is drawn perpendicular to the inferior end plate of the apical thoracic vertebra. Another line is drawn between two points that bisect the head and neck of the rib articulating with the apex. The angle between the perpendicular line (a) and the rib line (b) is measured. The same procedure is repeated for the rib on the opposite side. The concave-convex side angles are equal to the RVAD. (Modified from Mehta MH. The rib-vertebra angle in the early diagnosis between resolving and progressive infantile scoliosis. J Bone Joint Surg Br. 1972;54[2]:230–243.)

perpendicular from the vertebral end plate and a line down the center of the rib. The measurement is calculated on the convex and concave side, and the final **rib vertebral angle difference** (RVAD) is calculated by subtracting the convex side from the concave side (Fig. 720.3). A curve with an RVAD <20 degrees will resolve in about 80% of cases, whereas one with an RVAD >20 degrees will progress in over 80% of cases. Curves that resolve typically do so before 2 years of age.

Several factors affect the rate of curve progression in patients with AIS. Curves are more likely to progress in more skeletally immature patients with significant growth remaining. Findings associated with significant growth remaining are younger age, premenarchal status, Tanner stage I or II, Risser sign (a radiographic measurement of ossification of the iliac crest) of 0 or 1, and Sanders Maturity Scale values of 1–4. The Sanders Skeletal Maturity Staging System examines skeletal maturity using a single PA radiograph of the left hand and associates this value with current curve magnitude. Patients are staged from S1–S8, with S1 being the most immature and S8 indicating early maturity. Higher magnitude curves in more skeletally immature patients are more likely to progress.

Other factors affecting curve progression are the current curve magnitude, curve pattern, and patient sex. Three-dimensional spinal measurements of vertebral wedging, axial rotation, and torsion have been correlated to curve progression. In general, female patients are more likely than males to have curves that progress. Younger, premenarchal

females with curves between 20 and 30 degrees have a significantly higher risk of progression than do females 2 years after menarche with similar curves, demonstrating the significance of age on progression. In fact, the older group is unlikely to have any progression at all whereas premenarchal females with the same curve are likely to progress. Thoracic curves <30 degrees rarely progress after skeletal maturity, while those >45 degrees may progress approximately 1-2 degrees annually past skeletal maturity, and surgical stabilization is commonly offered.

Functionally, there are not many significant, clinically detrimental effects of smaller curves. There is conflicting literature regarding the exact curve magnitude and curve morphology in idiopathic thoracic scoliosis that leads to cardiopulmonary impairment. Thoracic curves of 50-70 degrees and greater have been associated with pulmonary impairment, although magnitude of curve alone cannot fully predict pulmonary function. Exercise capacity indicators, including heart rate, peak oxygen intake, and work rate, were not affected by thoracic curve magnitude, while FEV₁ was influenced in a prospective study of AIS patients. Factors such as thoracic kyphosis, curve stiffness, location of curve apex, and degree of vertebral rotation may also impact pulmonary function. Surgical correction is correlated with improved total lung capacity in patients with severe restrictive pulmonary function preoperatively.

Long-term studies have demonstrated that back pain is common in patients with scoliosis, although there is no definitive connection between pain and the curve magnitude or location. Furthermore, nearly 70% of patients with pain reported low or moderate severity of symptoms, stating that the pain does not interfere with normal activities.

TREATMENT OF IDIOPATHIC SCOLIOSIS

Treatment options include observation for small curves, bracing, and surgical care. Vitamin D deficiency is common in patients with adolescent idiopathic scoliosis, so evaluation and supplementation if appropriate should be considered. Brace treatment decreases the incidence of curve progression. The BraIST study, examining the effect of Boston braces in patients treated for 18 hours a day, was stopped before study completion because the benefits of bracing became so clear that it was unethical to continue patients in the nonbraced control arm of the study. Treatment success (preventing curve progression to 50 degrees) in the bracing group was 72%, whereas only 48% of those patients observed without bracing avoided progression to the surgical range. Other types of bracing have also been used, including the Providence night bending brace and the Rigo Chêneau Brace. When discussing bracing with families, it is important to understand that bracing in AIS does not lead to curve resolution or other measures of decreased magnitude but rather limits further progression. Additionally, while ~30% of patients who are braced will still require surgery, this does not necessarily mean that bracing was unsuccessful: without a brace, the curve may have progressed more rapidly or to an even higher magnitude, potentially requiring either an earlier surgery or more extensive fusion.

The bracing success rate depends on the amount of growth remaining. For example, patients with infantile or juvenile scoliosis are much more likely to require a surgical procedure than those with adolescent scoliosis and limited remaining growth. Patients at Risser 0 who are very skeletally immature are at a higher risk of surgery even if they are braced. It is recommended that these skeletally immature patients with curves that are otherwise thought of as small magnitude (>30 degrees) should be braced full time for a minimum of 18 hours daily. In addition to the effect of skeletal maturity, adherence with the recommended protocol for wearing the brace will influence the outcome. Adherence can be a challenge in the adolescent population. To better counsel parents and patients on their adherence, braces can be fitted with sensors to monitor duration of wear, and surgeons can review this data with families during follow-up appointments.

Braces are offered for treatment of skeletally immature patients with curves >30 degrees at the first visit or in patients who are being followed and have developed progression of their curvature beyond 25 degrees. Bracing is ineffective in curvatures >45 degrees because these patients have already reached the threshold for surgical intervention.

The brace is worn until complete cessation of growth in males, but in females, weaning from the brace may be considered when the patient is more than 2 years postmenarchal, is a Risser 4 or greater, and has grown less than a centimeter over the previous 6 months. Some practitioners will continue with the bracing beyond these parameters and base their weaning on the Sanders scale and/or assessment of the maturity of the distal radius and ulna, especially when the curve is more than 40 degrees because these curves are thought to have a significant incidence of progression after bracing has been completed. There also has been interest in using the Schroth method, which involves physical therapy in addition to a bracing program. While several studies have suggested that the Schroth method may enhance the success of a bracing program, further study will be required to make definitive recommendations.

Serial body casting (**Mehta casting**) can be performed in patients with early-onset scoliosis to minimize the risk of curve progression and potentially delay the necessity of growing spine procedures. In some cases, the scoliosis can be permanently corrected without the need for long-term bracing or surgery. Although most patients can tolerate casting well, the treatment is labor intensive, and there may be a negative impact on health-related quality of life for patients and their caregivers during and potentially after casting. Nonetheless, this quality-of-life effect must be carefully weighed against the risk of increased complications in patients who begin earlier growth-sparing spine surgery. One study found the risk of unplanned reoperation was 3 times higher in those who had growth-sparing spine surgery before age 3 when compared with those who were able to delay surgery.

Traditional surgical treatment involves spinal instrumentation and fusion and is usually recommended for skeletally immature patients with progressive curves >45 degrees and skeletally mature patients with curves >50 degrees. Some surgeons will also consider surgery for lumbar curves >35 degrees, particularly if associated with truncal imbalance. The goals of surgery are to arrest progression of the deformity, to improve cosmesis, and to achieve a balanced spine, all while minimizing the number of vertebral segments that are stabilized and thereby preserving as much motion as possible.

Implants including pedicle screws, sublaminar wires or bands, and hooks are attached to two longitudinal rods (Fig. 720.4). All implants function by allowing the application of mechanical forces to the spine, correcting the deformity in both the frontal and lateral planes to achieve normal frontal and sagittal spinal balance. Pedicle screw constructs also allow for derotational maneuvers, correcting the rib prominences associated with the axial component of the deformity. After instrumentation, the spine is decorticated, and bone graft is placed for the fusion portion of the procedure. The strength of modern spinal implants maintains correction without requiring a postoperative brace in most cases.

Most procedures are performed posteriorly using pedicle screw fixation, which affords excellent correction, especially of the rotational component of the deformity. Posterior osteotomies are often added to enhance flexibility and improve the degree of correction in stiffer curves. Anterior spinal releases requiring a thoracotomy are performed infrequently as a result of the efficacy of pedicle screw instrumentation. Open anterior thoracic and thoracolumbar procedures violate the chest wall and often the diaphragm. Pulmonary function may take up to 2 years to return to normal values. Although thoracoscopic techniques may be used to perform anterior spinal release with or without instrumentation and fusion, their use has been limited because of the efficacy of posterior pedicle screw constructs. However, patients with conditions such as neurofibromatosis and myelomeningocele have a higher likelihood of achieving a nonunion of their fusion, and an anterior fusion may be considered in addition to the posterior fusion in these groups. Additionally, patients with severe, neglected deformities may still benefit from combined anterior and posterior procedures.

Younger patients, in whom the triradiate cartilage remains open, are at risk for “crank shafting,” or progressive deformity due to continued anterior spinal growth, after a posterior fusion. Traditionally, these patients were treated by simultaneous anterior fusion to remove this growth potential; however, the rigidity of pedicle screw constructs has negated the need for this additional surgery. While an anterior fusion

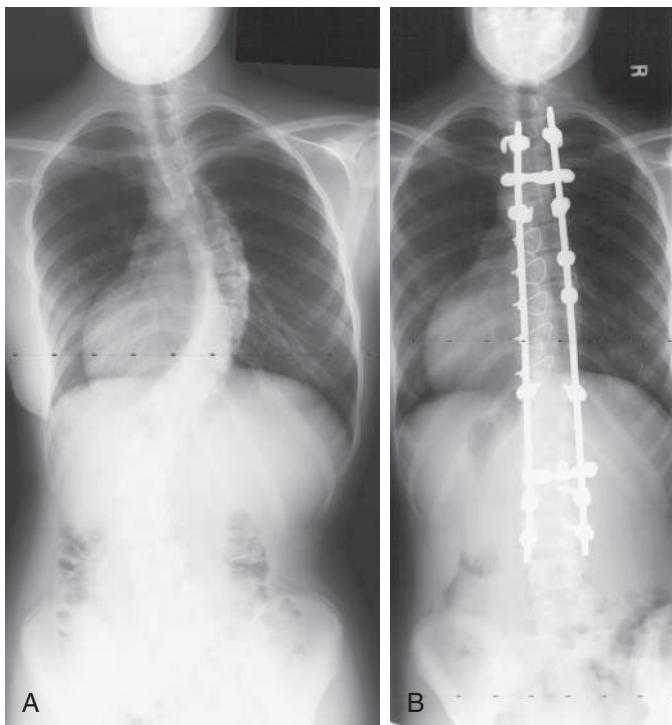


Fig. 720.4 Preoperative standing posteroanterior radiograph of a 14-yr-old female who was skeletally immature and developed a 68-degree right thoracic and a 53-degree left lumbar scoliosis (A). Her trunk was shifted to the right, and the left shoulder was slightly depressed. Based on the risk of future progression, she was treated by an instrumented posterior spinal fusion from T3 to L3 with correction of the right thoracic curve to 20 degrees and the left lumbar curve to 10 degrees (B). Coronal spinal balance was restored, and shoulder height was maintained.

with instrumentation can be considered for idiopathic thoracolumbar and lumbar curves, the posterior approach with pedicle screw fixation is being used more frequently to avoid the need for anterior surgery and chest wall violation.

Very young patients with growing spines are not candidates for definitive **posterior spinal fusion**, as this will limit their lung capacity. A commonly employed simple measurement of thoracic height (a vertical line drawn from T1-T12) can help guide treatment decisions, with fusion not recommended for patients with a thoracic height <22 cm.

In patients with remaining thoracic growth, growing spine procedures are recommended when surgical intervention is required. The most commonly used implants are **growing rods** (traditional and magnetic) and the **vertical expandable prosthetic titanium rib (VEPTR)**.

Growing rods have fixation points placed at the proximal and distal ends of the spinal deformity, which are then linked to subcutaneous expandable rods, spanning the length of the deformity (Fig. 720.5). These fixation points can be pedicle screws or hooks that affix to the posterior elements of the spine. Traditional growing rods require additional minor operations to lengthen the rods, performed about every 6–8 months. **Magnetically controlled growing rods (MCGRs)**, once inserted, can be lengthened in the clinic using an external device, thereby eliminating the need for further surgeries. Even with MCGR, complications are relatively common, with 39% of patients experiencing at least one complication, including rod breakage, screw/hook failure, failure of the rod to lengthen, and surgical site infection (though the risk of infection is lower than in traditional growing rods). Whether patients have traditional or magnetic growing rods, a final fusion is usually necessary once they have sufficient thoracic height or attain skeletal maturity. In selected cases in which the device is stable and the curve is well controlled once patients have achieved adequate pulmonary maturity and chest wall growth, observation

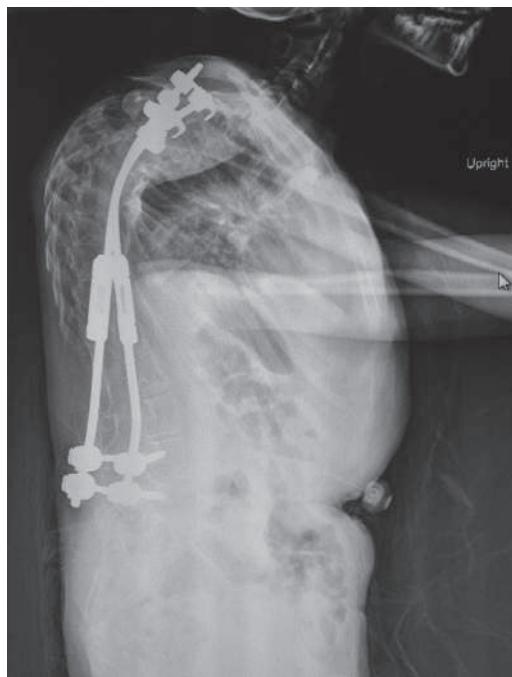


Fig. 720.5 A postoperative lateral radiograph of a skeletally immature patient with severe syndromic scoliosis after placement of growing rods.

has been selected rather than definitive fusion. Minimal correction is achieved when converting growth sparing implants to definitive spinal fusion because there is local osteopenia and usually fibrous or osseous fusions at a subset of spinal segments. In patients who have elected observation rather than conversion to a fusion, the indications for conversion would include implant failure/loss of correction and/or progression of curvature.

The VEPTR (Fig. 720.6) helps young children with thoracic insufficiency syndrome and is also used for early-onset scoliosis in patients with congenital or neuromuscular diagnoses. Long-term survival rates are favorable for these extremely severe deformity patients treated by VEPTR, though the risk of implant-related complications is substantial. Surgery in these young syndromic patients carries a substantial risk of complications, and one study reported a complication rate of nearly 85% with a mortality rate of over 15% over the entire course of operative treatment for early-onset scoliosis.

Significant interest remains in developing surgical techniques to treat AIS that can avoid spinal fusion. One fusionless technique currently used is anterior vertebral body tethering, consisting of a flexible cord attached with screws to affected vertebrae, allowing for correction of a curve dynamically by limiting growth on the curve convexity. Although the device most certainly limits motion to some extent, one would expect greater motion than patients treated with fusion. The ideal indications for tethering remain unclear, though commonly employed criteria are patients age 9–15 years with thoracic curves of 40–67 degrees and Risser stage of ≤1.

A meta-analysis of tethering found that pooled complication rates were 26% for patients treated with a tether versus 0.6% for those treated with a standard posterior spinal fusion. Additionally, the mean reoperation rates in studies that had at least 3 years of follow-up were 24.7% in patients treated with tethers versus 1.8% in posterior spinal fusion patients. Patients treated with posterior spinal fusion have a mean revision rate at 10 years of 7.5% (i.e., >90% are definitively treated with a single procedure).

Another novel fusionless treatment is the ApiFix, which is an expandable, ratcheting, hinged rod connected to a cluster of pedicle screws above and below a curve. The device is placed posteriorly and can allow more motion than traditional fusion techniques, but this has been associated with a 50% complication rate within 2 years, including

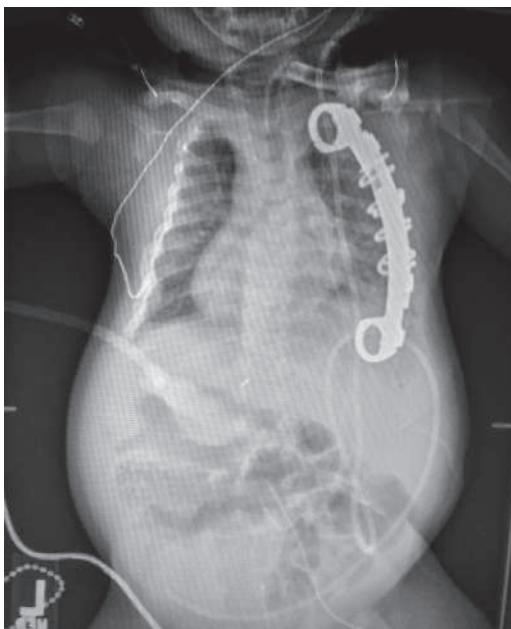


Fig. 720.6 A postoperative posteroanterior radiograph of a patient with Jeune syndrome after placement of a right rib-to-rib VEPTR (vertical expandable prosthetic titanium rib).

implant breakage, failure of the ratchet mechanism, osteolysis, and bacterial seeding of implants.

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720.2 Congenital Scoliosis

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Congenital scoliosis is a spinal deformity that results from abnormal development of the vertebrae. Asymmetric spinal growth due to one or more vertebral anomalies leads to spinal curvature. Although the malformation is present at birth, it may not become clinically apparent until a later time as growth progresses.

Etiology

Embryologic development of the spine begins at the fifth week of gestation. An insult to the normal developmental process occurs, resulting in abnormal growth of one or more vertebrae. Oftentimes, this abnormal development is associated with additional developmental anomalies or known syndromic conditions, including Alagille, Jarcho-Levin, Klippel-Fiel, Goldenhar, and VACTERL syndromes.

Associated Conditions

It is common for children with congenital scoliosis to have associated malformations in other organ systems that must be ruled out. Genitourinary abnormalities are identified in 20–40% of children with congenital scoliosis and include unilateral renal agenesis, ureteral duplication, horseshoe kidney, and genital anomalies. Approximately 2% of these patients have a silent obstructive uropathy. Renal ultrasonography should be performed early on in all children with congenital scoliosis; other studies such as CT or MRI may also be required.

Cardiac anomalies are identified in 10–54% of patients. A thorough cardiac examination should be performed as well as a referral to pediatric cardiology for consideration of echocardiography.

Intraspinal anomalies are identified in approximately 15–40% of patients. Spinal dysraphism is the general term applied to such lesions (see Chapters 631 and 689). Examples include diastematomyelia, split cord malformations, intraspinal lipomas, arachnoid

cysts, teratomas, dermoid sinuses, fibrous bands, and a tight filum terminale. **Cutaneous findings** that may be seen in patients with closed spinal dysraphism include hair patches, skin tags or dimples, sinuses, and hemangiomas. Infants with these cutaneous abnormalities overlying the spine may benefit from ultrasonography to rule out an occult spinal dysraphic condition. MRI is often delayed in older patients until a clinical indication is present, such as tethering of the spinal cord, which may present as back or leg pain, calf atrophy, progressive unilateral foot deformity (especially cavovarus), and problems with bowel or bladder function.

Classification of Congenital Scoliosis

Congenital scoliosis is classified by the type of developmental abnormality: either a **failure of formation** or a **failure of segmentation**. The deformities are then further described by the anatomic features of the affected vertebrae. Failure of formation results in wedge vertebrae or hemivertebrae. Failure of segmentation results in unilateral bar vertebrae or block vertebrae. Some instances of congenital scoliosis result from a combination of both failure of formation and failure of segmentation (Fig. 720.7). One or more bony anomalies may occur in isolation or in combination.

Natural History of Congenital Scoliosis

The risk of progression depends on the growth potential of each anomaly, which may vary considerably. Close radiographic follow-up is required. Progression of these curves is most pronounced during periods of rapid growth associated with the first 2–3 years of life and adolescence.

The anatomic characteristics of the malformed vertebra play a significant role in the progression of deformity. The most severe form of congenital scoliosis is a *unilateral* unsegmented bar with a contralateral hemivertebra. In this anomaly, the spine is fused to the side of the unsegmented bar but also has a growth center on the other side at the location of the hemivertebra at the same level. This combination of deformities in the bony spine results in a rapidly progressive curve. All affected patients usually require surgical stabilization. A unilateral unsegmented bar is also associated with significant progression and in most cases will require surgical intervention. An isolated hemivertebra must be followed closely, and many, but not all, of these will be associated with a progressive deformity that requires surgical intervention. In contrast, an isolated block vertebra has little growth potential and rarely requires treatment.

Treatment of Congenital Scoliosis

Early diagnosis and prompt treatment of progressive curves are essential. Bracing is not traditionally indicated for most congenital curves due to their structural nature, except in rare cases to control additional curves not associated with the bony abnormality or to attempt to delay surgery until a safer age for a surgical procedure. Once a bony abnormality is identified that is likely to progress, surgery is recommended before progression occurs, preventing development or further inevitable progression of spinal deformity. If the deformity has already developed, surgical correction is difficult to achieve and the risk of neurologic complications is high.

Surgical techniques depend on the curve anatomy, flexibility, patient age, and surgeon preference. Young patients with growing spines may benefit from a growing spine procedure to allow further growth while limiting curve progression. In terms of definitive fusion, an anterior and posterior spinal fusion was often historically required, though with pedicle screw constructs, a posterior fusion can be sufficient. A convex hemiepiphiodesis is an option for selected cases with milder curves and younger patients, fusing only one side of the spine to allow some correction of the deformity by permitting growth on the noninvolved side of the curve. Complete excision of a hemivertebra along with fusion of a short segment of the spine through a posterior approach has been performed with greater frequency and often in early childhood. A definitive fusion is still required for many progressive curvatures at skeletal maturity.

Adolescents with a congenital etiology of their spinal deformities are at higher risk of developing in-hospital complications than those with

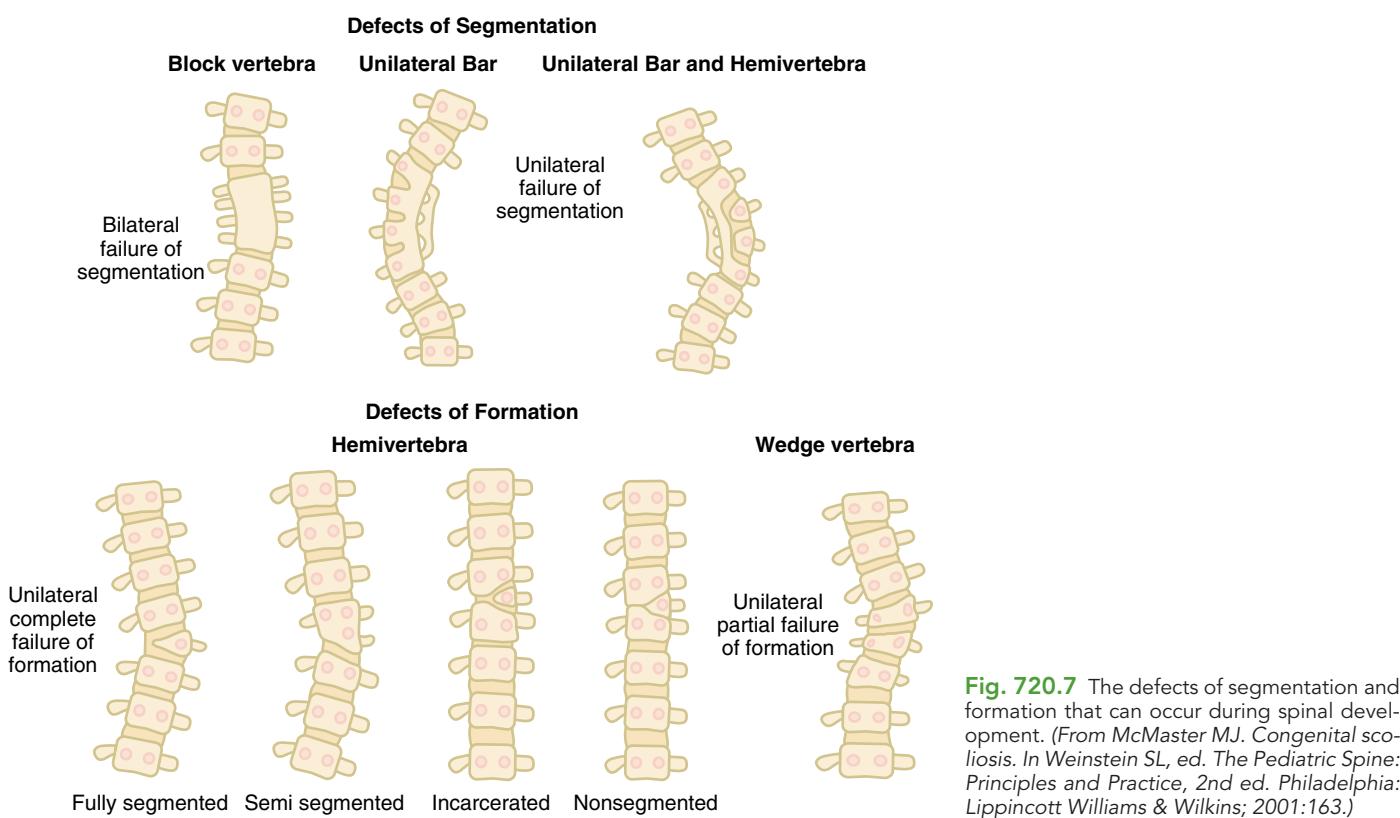


Fig. 720.7 The defects of segmentation and formation that can occur during spinal development. (From McMaster MJ. Congenital scoliosis. In Weinstein SL, ed. *The Pediatric Spine: Principles and Practice*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2001:163.)

idiopathic scoliosis, including shock, infection, and acute respiratory distress syndrome.

SPECIAL CIRCUMSTANCE: THORACIC INSUFFICIENCY SYNDROME

When multiple levels of the thoracic spine are involved in the presence of fused ribs, a progressive three-dimensional deformity of the chest wall may impair lung development and function. This development is termed **thoracic insufficiency syndrome**, when the chest wall is unable to support normal respiration, which can result in decreased life expectancy ([Chapter 467.5](#)).

Thoracic insufficiency syndrome may be seen in patients with several recognized conditions such as **Jarcho-Levin syndrome** (spondylocostal or spondylothoracic dysplasia) and **Jeune syndrome** (asphyxiating thoracic dystrophy) as well as patients with early-onset scoliosis (idiopathic, neuromuscular, or congenital) and severe spinal deformities in older patients. These difficult cases are treated with **expansion thoracoplasty**, in which the thoracic cage is gradually expanded over time by progressive lengthening of the chest wall on the concavity of the spinal deformity (or in some cases on both sides of the spine). The procedure involves an opening wedge thoracostomy, followed by placement of a VEPTR. The implant is then lengthened at regular intervals ([Fig. 720.8](#)). The primary goal is to gradually correct the chest wall deformity to improve pulmonary function, and a secondary goal is correction of an associated spinal deformity. In patients with associated fused ribs, insertion of a VEPTR with an opening wedge thoracostomy results in improved pulmonary function. VEPTR also has been used successfully in patients with early-onset congenital scoliosis. Complications are frequent, and multiple procedures are required; however, this strategy offers hope for many patients with complex, challenging cases. The decision of whether to proceed with a final spinal arthrodesis once chest wall and pulmonary development are thought to be adequate will depend on the specifics of each case. Some patients may elect to be followed even after skeletal maturity if the implant remains in stable position. Further research will be required to answer this and other questions.

720.3 Neuromuscular Scoliosis, Genetic Syndromes, and Compensatory Scoliosis

R. Justin Mistovich and David A. Spiegel

NEUROMUSCULAR SCOLIOSIS

Scoliosis is frequently identified in children with neuromuscular diseases such as cerebral palsy, muscular dystrophies, myopathies, spinal muscular atrophy, Friedreich's ataxia, myelomeningocele, polio, and arthrogryposis. Children with spinal cord injuries are also at high risk to develop a progressive curvature. The etiology and natural history of these patients differ from idiopathic and congenital scoliosis. Most cases result from weakness and/or imbalance of the trunk musculature. Spasticity may also contribute to spinal curvatures. In some cases, such as myelomeningocele, coexisting congenital vertebral anomalies may be present, further contributing to curve development.

A spinal deformity is more common in patients with higher degrees of neurologic impairment, particularly those who are nonambulatory with inadequate control of their trunk. It is diagnosed in more than 70% of nonambulatory patients with cerebral palsy and over 90% of patients with Duchenne muscular dystrophy.

The diagnosis is suspected on physical examination. In nonambulatory patients, the most common curve pattern is a long, sweeping C-shaped thoracolumbar or lumbar curve ([Fig. 720.9](#)). The curve is typically associated with pelvic obliquity, which may have an impact on seating balance. In contrast, ambulatory patients with diagnoses such as Friedreich ataxia may have curve patterns more similar to that of idiopathic scoliosis.

In ambulatory patients, the examination is similar to the physical examination for idiopathic scoliosis. In nonambulatory patients, the back is inspected with the patient sitting upright. Any asymmetry should be noted. These patients often need manual support to maintain an upright position. If any progressive asymmetry is observed, sitting

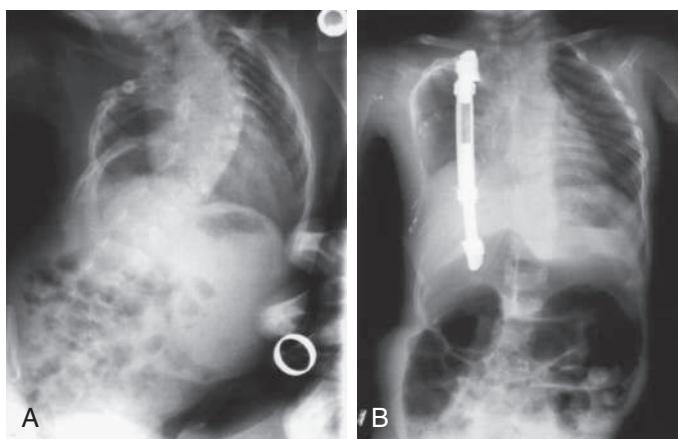


Fig. 720.8 A, Anteroposterior preoperative radiograph of a 7-mo-old infant with congenital scoliosis and fused ribs. A three-dimensional reconstruction of a CT scan of the chest of this infant estimated his lung volume to be 173.2 mL^3 . B, Anteroposterior radiograph after implantation of a vertically expandable prosthetic titanium rib and several expansions over 33 mo. The lung volume now measures 330.3 mL^3 , an increase of 90.7%. (From Gollogly S, Smith JT, Campbell RM. Determining lung volume with three-dimensional reconstructions of CT scan data: a pilot study to evaluate the effects of expansion thoracoplasty on children with severe spinal deformities. *J Pediatr Orthop.* 2004;23:323-328.)



Fig. 720.9 Imaging shows a long C-shaped curve with convexity to the left side and significant pelvic obliquity, a curve pattern often seen in patients with neuromuscular scoliosis. (From Pruthi S. *Scoliosis*. In: Coley BD, ed. *Caffey's Pediatric Diagnostic Imaging*, 12th ed. Philadelphia: WB Saunders; 2013: Fig 135-10B.)

PA and lateral radiographs should be obtained. Because prophylactic treatment or bracing cannot alter the natural history of the disease, our own preference is to establish the diagnosis clinically and obtain radiographs if the curve is noted to progress.

The clinical course of patients with neuromuscular scoliosis depends on the severity of neuromuscular involvement as well as the nature of the underlying disease process. Progressive diseases are often associated with progressive curvatures. The consequences of a progressive scoliosis in the neuromuscular population involve function, especially sitting and standing balance, and ease of hygiene and personal care. Pulmonary dysfunction may be expected with the gradual deformation

of the rib cage and vertebra-pelvic axis, as well as collapse of the spine with the pelvis impinging on the rib cage. Diaphragmatic function is impaired, and changes in chest volume and chest wall architecture will undoubtedly exacerbate the pulmonary dysfunction owing to underlying muscle weakness. Pulmonary function may be difficult to document in some patient populations, especially those with severe cerebral palsy. Additionally, patients with initial marginal ambulatory function may lose the ability to walk altogether as their scoliosis advances. Curves associated with pelvic obliquity result in asymmetric seating pressures, which may limit sitting endurance and may cause skin breakdown and decubitus ulcers. Patients may also experience pain from impingement of the rib cage on the iliac crest.

The treatment of neuromuscular scoliosis depends on the age of the patient, the underlying diagnosis, and the magnitude of the deformity. The goal is to achieve or maintain a straight spine over a level pelvis, especially in the nonambulatory population, and to intervene early before curve magnitude and rigidity become severe. Neuromuscular curves often continue to progress after skeletal maturity. Curves of $>40\text{-}50$ degrees will continue to worsen over time. Brace treatment does not affect the natural history of neuromuscular scoliosis, and standard braces used for idiopathic scoliosis are poorly tolerated in neuromuscular patients. A **soft spinal orthosis** may improve sitting balance and ease of care, although it does not ultimately change the natural history of the curvature.

A spinal **arthrodesis** should be offered to patients with progressive curvatures over 40-50 degrees. The indications will differ somewhat based on the underlying diagnosis. For example, patients with Duchenne muscular dystrophy are often offered surgery when their curves progress beyond 20-30 degrees, before their anticipated decline in pulmonary or cardiac function makes the procedure riskier or precludes their ability to tolerate surgery. Ambulatory patients with curvatures similar to those seen in idiopathic scoliosis are managed by principles similar to those used with idiopathic etiologies. Patients who are nonambulatory with pelvic obliquity are usually managed by a long spinal fusion extending from the upper thoracic spine to the pelvis, or the lower lumbar spine in selected cases. A brace is not required after this procedure. Treatment decisions must be individualized in nonambulatory patients with spastic quadriplegia and are based on loss of function, the potential to improve hygiene or personal care, and the desires of the family and/or caregivers. These treatment decisions are complex, and research has demonstrated the benefit of formal decision aids for families to assist with understanding treatment risks and benefits.

Although complications are relatively frequent in comparison to patients with nonneuromuscular curves, the available literature suggests that most patients benefit in terms of function and ease of care. Additionally, data suggest that corrective surgery for patients with neuromuscular scoliosis may improve weight gain postoperatively. It is important to identify risk factors for perioperative complications. Research studies have identified nonambulatory patients and those with curves ≥ 60 degrees as having a significantly increased risk of postoperative major complications, including ileus, pneumonia, infection, and wound problems. Gastrostomy (G)-tube dependence and increased blood loss were also found to be risk factors for postoperative complications. Baclofen pumps have not been associated with increased risk of complications. ASA classification ≥ 3 , BMI ≥ 95 th percentile, and extension of fusion to the pelvis have been found to be associated with postoperative infections. One study subclassified patients with Gross Motor Function Classification System (GMFCS) level 5 in terms of their risk for complications from spinal fusion. These patients have severe functional limitations and are at a high risk of perioperative complications, although not all are identical in terms of risk factors. They identified four subgroups, based on the associated presence of a G-tube, tracheostomy, history of seizures, and nonverbal status. Patients with none of these risk factors were subclassified as 5.0; one associated risk factor was 5.1; two were 5.2; and three or more were 5.3. The rate of major complications for patients with 5.0 GMFCS levels

was 12%, whereas patients with 5.3 GMFCS level had a 49% rate of major complications.

SYNDROMES AND GENETIC DISORDERS

This diverse group of diagnoses includes **neurofibromatosis** (see Chapter 636.1), **osteogenesis imperfecta** (see Chapter 742), connective tissue diseases such as **Marfan syndrome** (see Chapter 743) and **Ehlers-Danlos syndrome** (see Chapter 744), and **Prader-Willi syndrome** (see Chapter 99). Patients with these diagnoses should have their spine examined routinely during visits to their primary care physician. The follow-up and treatment are based on the age of the patient, the degree of deformity, whether progression has been documented, and the underlying diagnosis. Growth-sparing surgical strategies are appropriate in these diverse patient populations depending on curve onset. Each has unique aspects to their medical and surgical care, often with anatomic abnormalities such as dysplastic bone and dural ectasia, and as a group these diseases have a higher rate of complications related to bleeding, wound healing, infection, neurologic dysfunction, nonunion, and the development of progressive curvatures above or below the instrumented segments in comparison with patients requiring surgery for idiopathic scoliosis. Knowledge of the patient's genetic disorder, including prognosis and life expectancy, is important when determining whether surgical correction is appropriate.

COMPENSATORY SCOLIOSIS

Leg-length inequality is a common clinical diagnosis and is usually associated with a small compensatory lumbar curvature (see Chapter 717). This is one cause of false-positive screening examinations. Patients with leg-length inequality may have the pelvis become tilted toward the shorter limb and subsequently develop an associated lumbar curve. The apex of the curve points toward the short leg. There is little evidence to suggest that a small compensatory lumbar curve places the patient at risk of progression or back pain. However, children with leg-length inequality may also have idiopathic or congenital scoliosis. A standing radiograph may be obtained with a block under the foot on the short side, which corrects the leg-length discrepancy and levels the pelvis. If the curvature disappears when the limb-length discrepancy is corrected, a diagnosis of a compensatory curve is made. An alternative imaging study is a PA radiograph with the patient seated.

In neuromuscular disorders such as polio (see Chapter 296) or cerebral palsy (see Chapter 638.1), an adduction or abduction contracture of the hip, described as a fixed infrapelvic contracture, may have an associated compensatory lumbar scoliosis to maintain standing balance. For patients who ambulate, a 10-degree fixed contracture will result in up to 3 cm of apparent leg-length discrepancy.

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720.4 Kyphosis

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

The normal thoracic spine has 20–50 degrees of kyphosis from T3–T12 using the Cobb method on a standing lateral radiograph of the spine. A thoracic kyphosis in excess of the normal range of values is termed **hyperkyphosis**. Patients with hyperkyphosis may present with cosmetic concerns, back pain, or both. A flexible or postural kyphosis may be overcorrected voluntarily or with postural adjustment; however, a rigid kyphosis cannot be corrected passively. Causes of rigid kyphosis include **Scheuermann disease** and congenital kyphosis, among others. Table 720.2 lists conditions associated with hyperkyphosis.

Table 720.2 Conditions Associated with Hyperkyphosis

- Trauma causing spinal fractures
- Spinal infections resulting from bacteria, tuberculosis, and fungi
- Metabolic diseases such as osteogenesis imperfecta or osteoporosis
- Iatrogenic (laminectomy, spinal irradiation)
- Neuromuscular diseases
- Neoplasms
- Congenital/developmental
 - Disorders of collagen such as Marfan syndrome
 - Dysplasias such as neurofibromatosis, achondroplasia, and mucopolysaccharidoses

The evaluation and treatment depend on the underlying diagnosis, the degree of deformity, curve flexibility, whether the deformity is progressive, and severity of associated symptoms.

FLEXIBLE KYPHOSIS (POSTURAL KYPHOSIS)

Postural kyphosis is a common cosmetic concern and is most often recognized by parents or peers. Adolescents with postural kyphosis can correct the curvature voluntarily. A standing lateral radiograph will show an increase in kyphosis but no pathologic changes of the involved vertebrae. There is no evidence that postural kyphosis progresses to a structural deformity. Although mild aching discomfort is sometimes reported, there is no evidence that the condition leads to long-term symptoms, alterations in function, or reduced quality of life. The mainstay of treatment is reassurance. Physical therapy can be considered for muscular discomfort. Although core strengthening is certainly beneficial to most patients, no data suggest that a permanent alteration in alignment can be maintained. Neither bracing nor surgery plays a role in the management of this condition.

STRUCTURAL KYPHOSIS

Scheuermann Disease

Scheuermann disease is the most common form of structural hyperkyphosis and is defined by wedging of >5 degrees of three or more consecutive vertebral bodies at the apex of the deformity on a lateral radiograph. In addition, the apex of the thoracic kyphosis is lower than expected. Other radiographic findings include irregularities of the vertebral end plates and **Schmorl nodes**, which are herniations of the vertebral disk into the surface of the vertebral body. The etiology remains unknown but most likely involves the influence of mechanical forces in a genetically susceptible individual. Histologic specimens taken of patients with Scheuermann disease have shown a disordered pattern of endochondral ossification. However, it remains unclear whether these findings are the primary result of a genetic or metabolic pathologic process, or simply the secondary result of mechanical overload. The reported incidence varies from 0.4% to 10%, affecting males three times more frequently than females.

Physical Exam and Clinical Manifestations

The patient should be examined from the side. Hyperkyphosis of the thoracic spine will typically be associated with a sharp contour. The apex of the deformity will often be in the lower thoracic spine. Patients are unable to correct the deformity voluntarily. Pain is a relatively common complaint. It is typically mild and near the apex of the kyphosis. The symptoms are intermittent, rarely severe, and occasionally limit certain activities. Neurologic symptoms are uncommon.

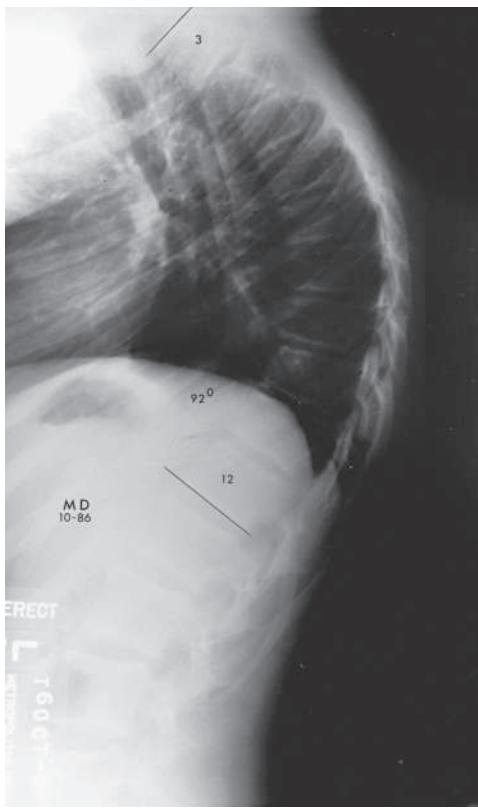


Fig. 720.10 Standing lateral radiograph of a 14-yr-old boy with severe Scheuermann kyphosis. This measures 92 degrees between T3 and T12. Note the wedging of the vertebrae at T6, T7, T8, and T9. The normal thoracic kyphosis is ≤ 40 degrees.

Radiographic Evaluation

The standard imaging protocol includes standing PA and lateral radiographs (Fig. 720.10). A specific, standardized technique in which the arms are folded across the chest is recommended for the lateral view. In addition to the diagnostic findings noted earlier, a mild scoliosis is commonly seen. Less frequently, a spondylolisthesis may be identified on the lateral radiograph.

Natural History

Treatment depends on the age of the patient, the degree of deformity, and whether any symptoms are present. Adolescent patients with Scheuermann kyphosis may have more complaints of back pain compared to other adolescents, but this often improves after skeletal maturity. A long-term follow-up study noted continued curve progression at about half a degree annually and poorer health-related quality of life compared to normative population values. Kyphotic deformities >90 degrees are more likely to be esthetically unacceptable, symptomatic, and progressive. Deformities more than 100 degrees may be associated with restrictive pulmonary dysfunction.

Treatment

There are few absolute guidelines for treatment, and decisions must therefore be individualized. Skeletally immature patients with mild deformity may benefit from a hyperextension exercise program, but the effects of this strategy on pain relief and spinal alignment, or the natural history, remain unknown. Patients with more than

1 year of growth remaining and a kyphosis of $>55\text{--}60$ degrees may benefit from a bracing program. A Milwaukee brace, which extends up to the neck, is recommended for curves with an apex above T7, whereas curves with a lower apex may often be treated by a thoracolumbar orthosis. The brace should be worn for up to 23 hours daily. Consideration may also be given to a serial casting or stretching program to gain flexibility before instituting the brace program. The goal of the brace is to prevent progression. A permanent improvement in alignment is seen less frequently. Skeletally mature patients with little or no pain and acceptable cosmesis are not treated. In patients with progressive deformity $>70\text{--}80$ degrees who are dissatisfied with their cosmetic appearance or have persistent back pain despite nonoperative measures, a spinal fusion may be considered. Patients treated operatively have less pain and greater satisfaction with their outcome compared to those treated nonoperatively.

An instrumented posterior spinal fusion from the upper thoracic to the mid-lumbar spine is commonly performed, with spinal osteotomies to allow compression of the posterior elements to facilitate deformity correction. These osteotomies allow for shortening of the spine, which should reduce the risks of neurologic complications. An alternative that was used with frequency in the past is combining an anterior spinal release (diskectomies and fusion) with the posterior spinal fusion. This strategy has been used less frequently because of increased complications, length of stay, and costs, in addition to the satisfactory outcomes associated with posterior only surgery. Procedures for kyphosis carry a higher risk than fusions performed for AIS.

CONGENITAL KYPHOSIS

Congenital kyphosis results from congenital anomalies of the vertebrae. In an anterior failure of formation (**type I**), a portion of the vertebral body fails to form. The resulting kyphosis is typically identified after birth and carries a high risk of progression and neurologic dysfunction. Spinal cord dysfunction commonly results from compression at the apex of the deformity. The second type of congenital kyphosis involves an anterior failure of segmentation, in which two vertebrae are fused (**type II**). The posterior elements of the spine continue to grow, but the anterior spine does not, resulting in a variably progressive kyphosis and a much lower risk of neurologic dysfunction. Patients must be followed closely, and treatment is required in a significant number of cases. Similar to congenital scoliosis, abnormalities of other organ systems should be ruled out.

The treatment depends on the type of malformation, the degree of deformity, and whether neurologic symptoms are present. Bracing is ineffective, and surgical treatment is the only option for progressive curves. Because the natural history is poor for type I deformities and neurologic deterioration is likely, spinal fusion is usually performed shortly after the diagnosis is made. The surgical goals are to prevent or treat kyphotic deformities to restore adequate spinal alignment, while avoiding neurologic deterioration and complications and maximizing spinal growth to the extent possible. This usually involves some form of limited spinal fusion, which may include anterior and/or posterior components, with or without resection of the vertebral remnant, and spinal instrumentation. Ideally, only a short segment of the spine will be fused to try to maximize trunk height. Deformities resulting from anterior failure of segmentation also require spinal stabilization in some cases, but progression is typically slower, and patients are often followed over years to determine whether surgical stabilization will be required.

720.5 Back Pain in Children

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Back pain is a frequent complaint in pediatric and adolescent patients, with studies demonstrating single-year prevalence rates between 7% and 58% of adolescents. An epidemiologic cross-sectional survey found 33.7% of children 10–18 years old experienced back pain within the prior year, with 8.9% of them describing the pain as severe. Risk factors for back pain include increasing growth, female sex, family history, overuse injury resulting from sport participation, manual labor, mobile phone usage of more than 10 hours per week (back and neck pain), and possibly carrying a heavy backpack. Patients with scoliosis commonly have back pain; up to 25% may rate this as severe. The pain may be linked to anxiety, depression, and/or substance misuse (smoking, alcohol); psychosocial factors are often underappreciated. Younger patients are felt to have a greater likelihood of a pathologic diagnosis, and therefore a more aggressive workup has been suggested. The incidence of both pediatric and adolescent back pain has increased, whereas the proportion of patients having diagnosable pathology is decreasing, with 75–80% of patients having a negative workup. These trends add further complexity to determining the proper approach to diagnosis and treatment. The differential diagnosis is extensive (Table 720.3). Although the likelihood of serious pathology is low, a complete history and careful physical exam must be performed on all patients (Table 720.4).

CLINICAL EVALUATION

Providers should take a full history, identifying the location, character, and duration of symptoms. Any history of acute trauma or repetitive physical activities should be sought. It is important to identify patients with at-risk athletic pursuits, including football linemen or gymnasts who have a high incidence of spondylolysis and spondylolisthesis. Symptoms consistent with a neoplastic or infectious etiology include pain that is constant or unrelenting, not relieved by rest, and wakes the patient from sleep. Fevers, chills, night sweats, or constitutional symptoms of weight loss or malaise are additional red flags for infectious or neoplastic processes (see Table 720.4).

Symptoms of neurologic dysfunction must also be uncovered. Patients should be questioned about the presence of any radicular symptoms, gait disturbance, muscle weakness, alterations in sensation, muscle atrophy, and changes in bowel or bladder function.

The physical examination includes a complete musculoskeletal and neurologic assessment. The patient should be adequately undressed for the clinical exam. The provider should inspect the patient from the back and the side, identifying any changes in alignment in the frontal or sagittal plane. Assessment of range of motion in flexion, extension, and lateral bending should be performed. Recall that pain with extension suggests pathology within the posterior elements of the spine, such as spondylolysis. Forward flexion will exacerbate pain linked to abnormalities of the anterior column of the spine (vertebral body or disk), such as a herniated disk or diskitis.

Palpation will reveal any areas of point tenderness over the posterior bony elements of the spinal column or the muscles and identify muscle spasm or strain.

Because pain may be referred from a nonspine region, an abdominal examination should be performed, and a gynecologic evaluation should also be considered. Pathology at the sacroiliac joint may also mimic low back pain. This joint should be stressed by compression of the iliac wings or by external rotation at the hip (Faber test).

A detailed neurologic examination should be performed, including manual muscle testing, sensation, proprioception, and reflexes. The patient should be examined for myelopathy by performing the Babinski test, assessing for hyperreflexia, and checking for sustained (more than three beats) of clonus. The superficial cutaneous abdominal reflex should be tested by gently stroking the skin on

Table 720.3 Differential Diagnosis of Back Pain

INFECTIOUS AND INFLAMMATORY DISEASES

- Spondylodiscitis*
- Vertebral osteomyelitis (pyogenic, tuberculous)
- Spinal epidural abscess
- Transverse myelitis
- Pyelonephritis*
- Perinephric abscess
- Pancreatitis
- Paraspinal muscle abscess, myositis
- Psoas abscess
- Endocarditis
- Pelvic osteomyelitis or myositis
- Pelvic inflammatory disease

RHEUMATOLOGIC DISEASES

- Pauciarticular juvenile idiopathic arthritis*
- Reactive arthritis
- Ankylosing spondylitis
- Psoriatic arthritis
- Inflammatory bowel disease
- Fibrositis, fibromyalgia

DEVELOPMENTAL DISEASES

- Spondylolysis*
- Spondylolisthesis*
- Scheuermann kyphosis*
- Scoliosis
- Chiari malformation type 1 with or without syringomyelia
- Spinal dysraphism
- Cauda equina syndrome

MECHANICAL TRAUMA AND ABNORMALITIES

- Muscle strain/sprain*
- Hip/pelvic anomalies (sacroiliac joint dysfunction)
- Herniated disk (rare)
- Juvenile osteoporosis (rare)
- Overuse syndromes (facet syndrome)*
- Vertebral stress fractures
- Vertebral compression fractures
- Limbus vertebra
- Lumbosacral sprain*
- Seatbelt injury
- Trauma (direct injury; e.g., motor vehicle crash)*
- Strain from heavy knapsacks
- Radiculopathy (sciatica)

NEOPLASTIC DISEASES

- Primary vertebral tumors (osteogenic sarcoma, Ewing sarcoma)
- Metastatic tumor (neuroblastoma, rhabdomyosarcoma)
- Primary spinal tumor (neuroblastoma, lipoma, cysts, astrocytoma, ependymoma)
- Malignancy of bone marrow (ALL, lymphoma)
- Benign tumors (eosinophilic granuloma, osteoid osteoma, osteoblastoma, bone cyst)

OTHER

- Disk space calcification (idiopathic, after diskitis)
- Conversion reaction
- Sickle cell anemia*
- Nephrolithiasis
- Hemolysis (acute)
- Hematocolpos
- Postprocedure pain after lumbar puncture

*Common.

ALL, Acute lymphocytic leukemia.

Modified from Marcdante KJ, Kliegman RM, Schuh AM. *Nelson Essentials of Pediatrics*, 9th ed. Philadelphia: Elsevier; 2023:774.

each of the four quadrants surrounding the umbilicus. Normally, the umbilicus will move toward the area stimulated. A normal examination includes symmetry in the response on both sides of the midline, even if the reflex cannot be elicited on either side. An abnormal test suggests the presence of a subtle abnormality of spinal cord function, most commonly syringomyelia. A straight leg

Table 720.4

Red Flags: Most Common Indications from History and Examination for Pathologic Findings Needing Special Attention and Sometimes Immediate Action

- Children younger than 18 yr old with considerable pain
- History of violent trauma
- Nonmechanical nature of pain (i.e., constant pain not affected by movement; pain at night)
- History of cancer
- Systemic steroid use
- Drug use
- HIV infection or other immunocompromised patients
- Unintentional weight loss
- Systemically ill, particularly signs of infections such as fever or night sweats
- Persisting severe restriction of motion or intense pain with minimal motion
- Structural deformity including scoliosis, Chiari malformation, tethered cord
- Difficulty with micturition (urinary retention)
- Loss of anal sphincter tone or fecal incontinence
- Progressive motor weakness or gait disturbance, paresthesias, pes cavus, foot drop, saddle anesthesia
- Marked morning stiffness
- Peripheral joint involvement
- Iritis, skin rashes, colitis, urethral discharge, or other symptoms of rheumatologic disease
- Inflammatory disorder such as ankylosing spondylitis suspected
- Family history of rheumatologic disease or structural abnormality

raise test should be done to check for nerve root tension secondary to a herniated disk, slipped vertebral apophysis, or other pathology. This examination should reproduce any neurologic symptoms distal to the knee.

MEDICAL DECISION-MAKING

A detailed history and physical exam are the most important components of the initial evaluation and should focus on identifying “red flags” and differentiating between mechanical and nonmechanical back pain (see Table 720.4). Findings consistent with a nonmechanical etiology warrant a more aggressive evaluation and/or prompt referral.

Patients with mechanical or muscular back pain and symptoms that are activity related and improve with rest are typically treated by rest for a few days or activity restrictions and nonnarcotic analgesics. Physical therapy for core strengthening should be considered if the acute symptoms do not resolve or if the pain is chronic. The patient should be asked to return for a follow-up appointment after 4–6 weeks. Plain radiographs are commonly obtained at the discretion of individual practitioners. However, if no red flags are present, providers may defer radiographs because of the cumulative adverse effects of radiation exposure. Patients presenting with red flags or those who have not improved after 6 weeks of conservative care necessitate further investigation.

RADIOGRAPHIC AND LABORATORY EVALUATION

When further workup is indicated, PA and lateral radiographs of the involved region of the spine are the initial images of choice. Some clinicians will also use oblique radiographs of the lumbar spine when spondylolisthesis is in the differential diagnosis. If plain radiographs are normal, advanced imaging modalities should be considered, including a three-phase technetium bone scan, a bone scan with single-photon emission computed tomography (SPECT) if spondylolisthesis is suspected, CT for viewing osseous detail, and MRI for viewing soft tissue detail or bony areas of inflammation.

When systemic signs or constitutional symptoms are present, a CBC, ESR, and CRP should be ordered. In certain cases, laboratory tests to evaluate for inflammatory diseases such as juvenile idiopathic arthritis, seronegative spondyloarthropathies, and ankylosing spondylitis are indicated.

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720.6 Spondylolysis and Spondylolisthesis

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Spondylolysis represents a defect in the pars interarticularis, the segment of bone connecting the superior and inferior articular facets in the vertebra. It is thought to result from repetitive hyperextension stresses, in which compressive forces are transmitted from the inferior articular facet of the superior vertebra to the pars interarticularis of the inferior vertebra. Supporting the mechanical theory, spondylolysis has never been described in nonambulatory adults. However, there may be a genetic association with 19–69% of affected patients having a first-degree relative also affected. A stress fracture, unilateral or bilateral, may progress to a spondylolysis. In many cases, this stress fracture does not heal, resulting in a pseudarthrosis, or false joint, and thereby allowing motion through this bony area where motion should not normally exist.

Spondylolysis is common in athletes who engage in repetitive spinal hyperextension, especially gymnasts, football interior linemen, weight-lifters, and wrestlers. Approximately 4–8% of the entire pediatric population is affected, making it the most common cause of back pain in adolescents when a diagnosis can be established. Patients with excessive lordosis in the lumbar spine may be predisposed to developing a spondylolysis, and a genetic component has also been suggested. The lesion is most common at L5, but it may be identified at upper lumbar levels as well.

Spondylolisthesis represents a forward slippage of one vertebra on another and is identified in approximately 4–5% of the population. The multiple causes of spondylolisthesis include dysplastic/congenital defects, isthmic (due to a pars stress fracture), trauma, and neoplasm. In children and adolescents, the most common types are dysplastic and isthmic. Between 5% and 15% of patients with spondylolysis will develop spondylolisthesis.

Spondylolisthesis is assessed on a standing lateral radiograph of the lumbosacral junction according to (1) the percentage of forward translation of one vertebra on the other, (2) the slip angle, measuring the rotation of the involved vertebrae in the sagittal plane, and (3) relative position of the sacrum during upright posture. A grade 1 slip of L5 on S1 has <25% of the width of the vertebral body of L5 translated anteriorly on S1. Similarly, grade 2 is 25–50%, grade 3 is 50–75%, and grade 4 is 75–100%. **Spondyloptosis**, or grade 5 spondylolisthesis, describes a complete displacement of one vertebral body on the level below. The slip angle, which demonstrates the degree to which the superior vertebra is flexed forward relative to the underlying vertebra, and the verticality of the sacrum both have a significant effect on sagittal balance or the relationship of the sagittal weight-bearing axis to the body segments. Abnormalities in sagittal spinal balance may be associated with compensatory flexion of the knees during ambulation, hamstring spasm and/or contracture, and back pain.

CLINICAL MANIFESTATIONS

Spondylolysis may occasionally be asymptomatic and diagnosed incidentally on imaging obtained for other reasons. It usually presents with mechanical low back pain that may radiate to the buttocks, with or without spasm of the hamstring muscles. Neurologic symptoms are rare in patients with spondylolysis. However, patients with spondylolisthesis may experience neurologic symptoms from compression or stretching of the nerve roots, causing radiculopathy or even the surgical emergency of cauda equina in which bowel and bladder function is affected.

PHYSICAL EXAM

Patients with spondylolysis often have discomfort with spinal extension or hyperextension. Provocative testing may include keeping the spine extended for 10–20 seconds to see if back pain can be reproduced. There may be discomfort with palpation of the spinous process of the involved vertebra. Patients with higher grades

of spondylolisthesis demonstrate loss of lumbar lordosis, flattening of the buttocks on visual inspection, and a vertical sacrum resulting from posterior rotation of the pelvis. A step-off may be palpated between the spinous processes of the involved vertebrae. Hamstring contracture is tested by measuring the popliteal angle. The hip is flexed to 90 degrees while fully extending the contralateral hip to the level of the pelvis. The knee is then passively extended, and the popliteal angle represents the angle between the thigh (vertical) and the lower leg axis. A careful, complete neurologic examination is essential because diagnosis of spondylolysis and spondylolisthesis is often delayed.

RADIOGRAPHIC EVALUATION

The initial evaluation of the lumbar region should include high-quality AP and lateral radiographs. Some authors also prefer to obtain oblique radiographs, which demonstrate the classic "Scotty dog" finding on the pars interarticularis. The lumbar spine in oblique radiograph projections normally appears to form the figure of a "Scotty dog" (i.e., Scottish terrier), with the transverse process forming the nose, the pedicle forming the eye, and the pars interarticularis forming the neck; in spondylolysis, the pars interarticularis will have a defect or a break, mimicking a "collar" on the radiograph. Standing PA and lateral radiographs of the entire spine are obtained if findings suggestive of scoliosis or hyperkyphosis are also present (Figs. 720.11 and 720.12). In patients with normal plain films, traditional imaging studies included a bone scan with SPECT to diagnose a spondylolysis during the earliest stage of a stress reaction, before the formation of a stress fracture or an established pseudarthrosis. The radiation exposure from this test, though, is substantial—bone scans have 7–9 times the radiation dose of two-view plain films. In comparison, CT scans carry only 2 times the radiation dose of two-view plain films. The sensitivity of MRI using STIR imaging is comparable to SPECT and led to a recommendation for MRI STIR rather than bone scans in acute cases in which plain films could not make a diagnosis. MRI sequences will demonstrate inflammation associated with an acute spondylolysis while avoiding radiation exposure. A CT scan with thin cuts may provide additional information to establish the presence of a pars defect and may be indicated in chronic, refractory cases. MRI is also indicated in the presence of signs or symptoms of cauda equina or nerve root involvement.

TREATMENT

The asymptomatic patient with spondylolysis requires no treatment. Patients with pain are treated initially by activity modification, physical therapy for core strengthening, and analgesic medications. The use of a lumbosacral orthosis, which immobilizes the spine in slight flexion to decompress the posterior elements, may lead to a faster resolution of symptoms, though a recent SRS Evidence Based Medicine Committee report determined that the benefit of bracing is not well established. This orthosis is typically worn for 3–4 months. Participation in sports or other activities that exacerbate pain should be restricted until the symptoms have resolved. Providers should consider checking a vitamin D level in patients with spondylolysis and treating if deficient.

Most patients experience resolution of their symptoms even though the spondylolysis heals in only a small number of patients. Surgery should be offered for chronic, refractory back pain when conservative measures have failed. For those with spondylolysis at L5, a posterior spinal fusion from L5 to S1 is indicated as the mobility at this joint is limited relative to that observed at higher levels in the spine. For the infrequent cases in which the defect is at higher levels in the lumbar spine, techniques for repairing the pseudarthrosis without fusion are considered.

Recommendations for the management of spondylolisthesis depend on the age of the patient, the presence of pain or neurologic symptoms, and the degree of deformity. For low-grade lesions, the management is similar to that for spondylolysis. Significant progressive slippage may occur in 3–5% of skeletally immature patients, and patients must be followed through skeletal maturity. Progression of deformity is

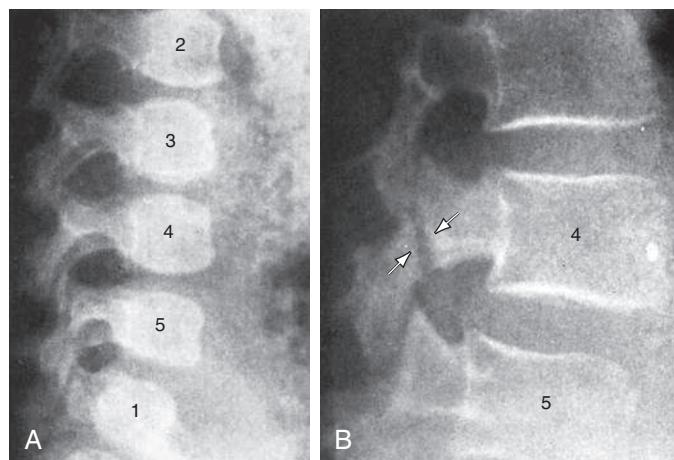


Fig. 720.11 A, Normal spine at 9 months of age. B, Spondylolysis in the L4 vertebra at 10 yr of age. (From Silverman FN, Kuhn JP. *Essentials of Caffrey's Pediatric X-ray Diagnosis*. Chicago: Year Book Medical Publishers; 1990:94.)

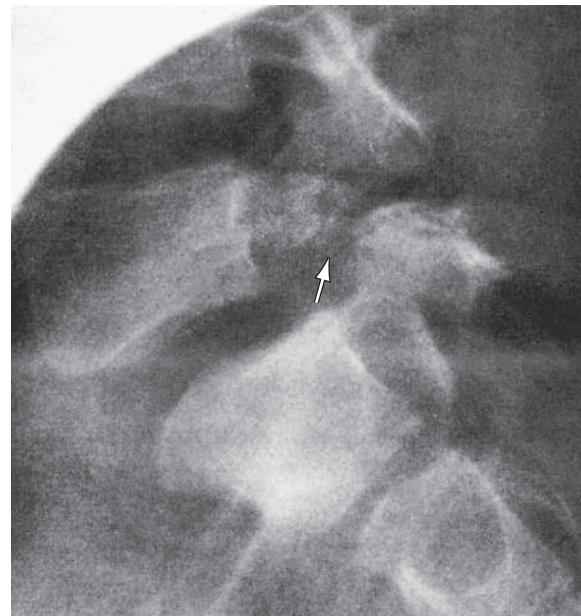


Fig. 720.12 Defect in the pars interarticularis (arrow) of the neural arch of L5 (spondylolysis) that has permitted the body of L5 to slip forward (spondylolisthesis) on the body of S1. (From Silverman FN, Kuhn JP. *Essentials of Caffrey's Pediatric X-ray Diagnosis*. Chicago: Year Book Medical Publishers; 1990:95.)

increased in higher grade slips and in cases of dysplastic spondylolisthesis. However, there is only a 1.4% incidence of progression after adolescence. Guidelines for the timing of follow-up, and whether or not to obtain routine radiographs at each follow-up, differ between individuals and institutions; we typically follow asymptomatic patients yearly with a standing lateral of the lumbosacral junction. Nonoperative management in minimally symptomatic or asymptomatic patients is appropriate, and delaying surgical treatment does not appear to worsen outcomes.

For low-grade slips with persistent symptoms despite nonoperative measures, an *in situ* posterior spinal arthrodesis is suggested. Additionally, patients with a more kyphotic slip angle have been shown to have poorer prognosis, although operative treatment did not significantly improve their outcome. The surgical approach for high-grade slips varies between surgeons and institutions. The main

principle is to stabilize the unstable segment of the spine, avoid neurologic complications, and restore adequate sagittal balance to the spine. The typical components of these complex procedures include (1) posterior decompression of the L5 and S1 nerve roots (laminectomy and takedown of pseudarthrosis), (2) instrumented posterior spinal fusion from L4 or L5 to S1 and occasionally the pelvis is included in the instrumentation, (3) discectomy at L5-S1 with placement of anterior column support (transforaminal cage or fibular allograft from sacrum to L5), and (4) reduction of the slippage by positioning the hips in extension or by an “instrumented reduction” using the spinal implants. Adding the anterior column support enhances rates of fusion. Reduction improves radiographic outcomes but may increase the risk of unplanned surgeries, pseudarthrosis (failure of fusion), and neurologic complications.

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720.7 Spine Infection

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Spondylitis, meaning inflammation of the vertebrae, is most commonly due to infectious or autoimmune processes. **Spondylodiscitis** is defined as a primary infection of the intervertebral disk (**diskitis**) with spread to the vertebrae (**osteomyelitis**). Based on MRI, some think the infection begins in the vertebral body with subsequent rupture into the disk space. The most common etiology is hematogenous seeding of bacteria, with the original infection of the well-perfused end plate extending into the disk and vertebral body. Spondylodiscitis is more commonly seen in children younger than 5 years of age but can occur at any age; it is often associated with vertebral body osteomyelitis. Patients in the younger age range have vascular channels between the vertebral end plate and the disk space, explaining the prevalence of diskitis with osteomyelitis.

Staphylococcus aureus is the most common organism causing spine infections. Other organisms include *Kingella kingae* and less often group A streptococcus and *Escherichia coli*. Rare causes of vertebral bone infection include tuberculosis (often multiple vertebral bodies), *Serratia marcescens*, brucellosis, and cat-scratch disease. Blood cultures have a sensitivity of only 30%. Percutaneous or less often open biopsy of the disk space is positive only 50–85% of the time; polymerase chain reaction is indicated for the diagnosis of *Kingella*. The differential diagnosis includes chronic recurrent multifocal osteomyelitis.

CLINICAL MANIFESTATIONS

A high index of suspicion is required to establish the diagnosis of infectious spondylodiscitis. Patients may experience back pain, abdominal pain, fever, or malaise. Fever is less common and may be present in only 30% of patients. Toddlers may develop a limp or refuse to walk, stand, or sit. In an effort to reduce the pain associated with spinal motion, the child will hold the spine in a rigid position. There may also be a paraspinal muscle spasm. Local point tenderness over the affected spinous process is common. There may be a “list” or leaning of the trunk when the patient is viewed from the front or back, and from the side there may be a loss of lumbar lordosis. Neurologic manifestations are rare and, if present, suggest that an epidural abscess may be present. The infection may drain beyond the spine to the paravertebral space and psoas muscles.

Spine flexion compresses the anterior elements of the spine and will elicit an increase in pain. Asking a child to pick up an object from the ground is a simple way to elicit this provocative test.

Although the white blood count may remain normal, the ESR is elevated in 80% of cases, and the CRP is also elevated.



Fig. 720.13 Spondylodiscitis. Sagittal T2-weighted (A) and coronal short tau inversion recovery (B) images demonstrate destruction of T7-T8 intervertebral disk with abnormal marrow signal in the adjacent vertebral bodies and associated paravertebral soft tissue phlegmon. (From Bossemani T, Huisman TAGM. Spine imaging. In: Walters MM, Robertson RL, eds. Pediatric Radiology: The Requisites, 4th ed. Philadelphia: Elsevier; 2017: Fig. 9.31, p. 345.)

RADIOGRAPHIC EVALUATION

The earliest radiographic finding is a postural loss of lumbar lordosis. Later characteristic features on plain radiographs are disk space narrowing, or loss of disk height, and irregularity of the adjacent vertebral end plates. However, these findings do not develop until 2–3 weeks after the onset of symptoms. The diagnosis may be established earlier using MRI. MRI is the most sensitive and specific imaging to diagnose osteomyelitis and to identify abscesses and/or neural compression (Figs. 720.13 and 720.14).

TREATMENT

Once the diagnosis is suspected clinically, the treatment involves symptomatic care and empiric anti-staphylococcal antibiotics, as *S. aureus* is the most common pathogen isolated. *Kingella kingae* is recognized as a common pathogen in patients from 6 months to 4 years of age. A first-generation cephalosporin (e.g., cefazolin) or semisynthetic antistaphylococcal penicillin (e.g., oxacillin) is recommended in areas where methicillin-resistant *S. aureus* (MRSA) is not prevalent. Clindamycin should be considered in areas where MRSA is more common. Some areas of the world report increasing clindamycin resistance among both methicillin-resistant and methicillin-susceptible *S. aureus* isolates, leading to consideration of vancomycin or linezolid. Blood cultures should be obtained before the administration of antibiotics. The antibiotic agent may be modified if blood cultures are positive. Symptomatic care includes rest and analgesics, antiinflammatory medications, and a spinal orthosis may also be considered. The typical antibiotic course is from 4–6 weeks. Data in osteomyelitis suggest that conversion from intravenous to oral agents may be acceptable after several days depending on the clinical course (see Chapter

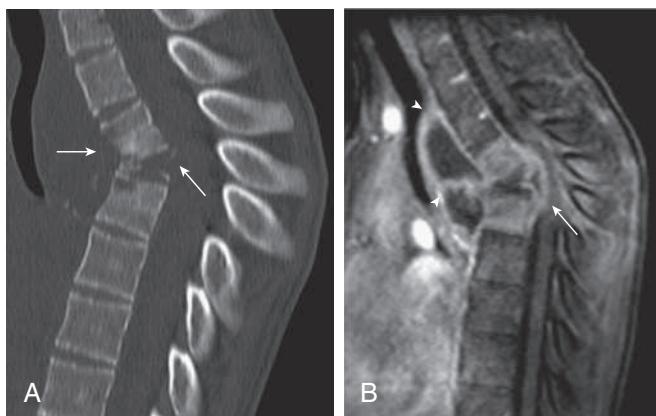


Fig. 720.14 Tuberculous vertebral osteomyelitis in 13-yr-old female with progressive loss of strength and coordination in legs. (A) Sagittal reformatted soft-tissue window images from a CT of the spine (B) sagittal fat-saturated postcontrast T1-weighted MR images of the thoracic spine demonstrate marked kyphosis at site of bony collapse at the level of the midthoracic spine (arrows in A and B), as well as surrounding soft tissue abscess (arrowheads in B) predominately anteriorly, at the same level. (Modified from Maddocks ABR, Pollock AN. In: Coley BD, ed. Caffey's Pediatric Diagnostic Imaging, 13th ed. Philadelphia: Elsevier; 2019: Fig. 44.8AC, p. 422.)

725). A CT-guided needle biopsy of the disk space can be considered. Although the diagnostic yield on cultures is low (20–40%), the pathologic findings may show acute inflammatory cells to establish the diagnosis (≥ 1 neutrophil per high power field). This intervention is often reserved for patients who do not respond to empiric antibiotics or when there are questionable diagnostic features. Surgical treatment is rarely required, and indications include establishing the diagnosis in patients who fail to respond to empiric antibiotics, and those in whom an abscess and/or neurologic involvement are identified.

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720.8 Intervertebral Disk Herniation/ Slipped Vertebral Apophysis

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Intervertebral disk herniation is the result of a tear in the outer layer of the vertebral disk, called the annulus fibrosus, which then allows for protrusion of the inner nucleus pulposus. At times, a free fragment of disk can rupture and compress the nerve roots or spinal cord. Bulging of the annulus without rupture may also be observed, resulting in back pain and occasionally radicular symptoms. Symptoms are due to either direct mechanical compression or a local inflammatory response.

Slipped vertebral apophysis, also called a posterior ring apophysis separation, is due to an injury and is only found in skeletally immature patients. A small fragment of bone from the posterior corner of the vertebral body apophysis avulses and may cause direct mechanical compression to the spinal cord or nerve root, similar to a disk herniation. (An apophysis is a normal outgrowth of bone with its own physis, or growth plate. Another example is the tibial tubercle.) Both disk herniations and ring apophysis separations can cause back pain, radicular symptoms (nerve root compression or irritation), or spinal cord compression.

Etiology

Predisposing activities for both conditions include heavy lifting, repetitive axial loading activities, and occasionally traumatic injury such as a fall. Approximately 30–60% of patients with symptomatic herniated disks have a history of a trauma or sports-related injury. Other

associations include preexisting disk degeneration, congenital malformation, and genetic or environmental factors. There may be a potential association between disk degeneration and the herpes virus. Missense pathogenic variants in collagen-encoding genes may be present in 80% of young patients with symptomatic lumbar disk herniations.

CLINICAL MANIFESTATIONS

Symptoms of intervertebral disk herniation or slipped vertebral apophysis in adolescents are similar to adult herniated disk symptoms. The major complaint is back pain, present in nearly 90% of patients. Over 30% of patients complain of **radicular symptoms** or radiating sciatic-type pain into the legs. The back pain is often made worse by coughing, a Valsalva maneuver, or sitting. Pain may be relieved by standing or back extension, which increases the disk space between vertebral bodies. Providers should inquire about weight loss, fever, or other constitutional symptoms to rule out an infectious or neoplastic etiology.

On physical examination, both paraspinal muscle spasm and a generalized spinal stiffness are common. Patients may lean toward the unaffected side to increase the size of the affected neural foramen, thereby partially relieving symptoms. This results in a reactive scoliosis—not a true spinal curve—that improves with symptom resolution. Although overt signs of neurologic involvement are absent in most patients, a positive straight leg raise test, causing radicular pain to shoot down the affected leg, is usually present. Pain is also worsened by spinal flexion.

It is critical to perform a full neurologic evaluation, including sensation to light touch, pinprick, and proprioception; muscle strength; and reflexes. Providers must also evaluate for perineal numbness, or saddle anesthesia. This finding, combined with changes in bowel or bladder function, is indicative of cauda equina syndrome, a surgical emergency in which the nerve roots at the caudal end of the spinal cord are compressed or damaged.

RADIOGRAPHIC EVALUATION

Radiographs often show loss of lumbar lordosis, which is due to muscle spasm, and sometimes a mild lumbar scoliosis. Other radiographic findings include degenerative changes and a loss of intervertebral disk height. MRI is the best study to establish the diagnosis of a disk herniation (Fig. 720.15). CT is especially helpful to visualize a partially ossified fragment associated with a slipped apophysis.

TREATMENT

The initial treatment is nonoperative in the vast majority of patients—even if symptoms or findings of radiculopathy are observed. Treatment focuses on rest, activity modification, NSAIDs, and physical therapy. An orthosis may provide additional symptomatic relief. Complete bed rest is not recommended. Epidural steroid injection (ESI) may be discussed with patients after approximately 6 weeks of symptomatic treatment if symptoms persist, though the evidence is not yet definitive. However, if patients elect to undergo an ESI, they should not have more than a single injection if the first did not provide any relief. Clinical experience has demonstrated that multiple injections are no more likely to provide relief than a single injection and expose patients to additional risks of infection, scarring, and neural injury. If a patient experiences substantial relief from an ESI and has a later recurrence of symptoms, consideration may be given for a repeat injection after performing a complete physical exam and ruling out any new pathology.

Surgical treatment should be considered when nonoperative measures have failed or when a profound neurologic deficit such as cauda equina syndrome is present or evolving. Unfortunately, children and adolescents respond less favorably to nonoperative therapy compared with adults, and a significant percentage will require surgical intervention. Although patients with disk herniation may improve with reduction in the local inflammatory response around the nerve root and also as the disk material loses water volume and shrinks, which eliminates mechanical compression, patients with symptomatic ring apophyseal separations have a bony fragment causing their symptoms and are unlikely to improve spontaneously.

The surgical technique involves removing a small area of the lamina via a posterior approach, called a **laminotomy**, which allows exposure

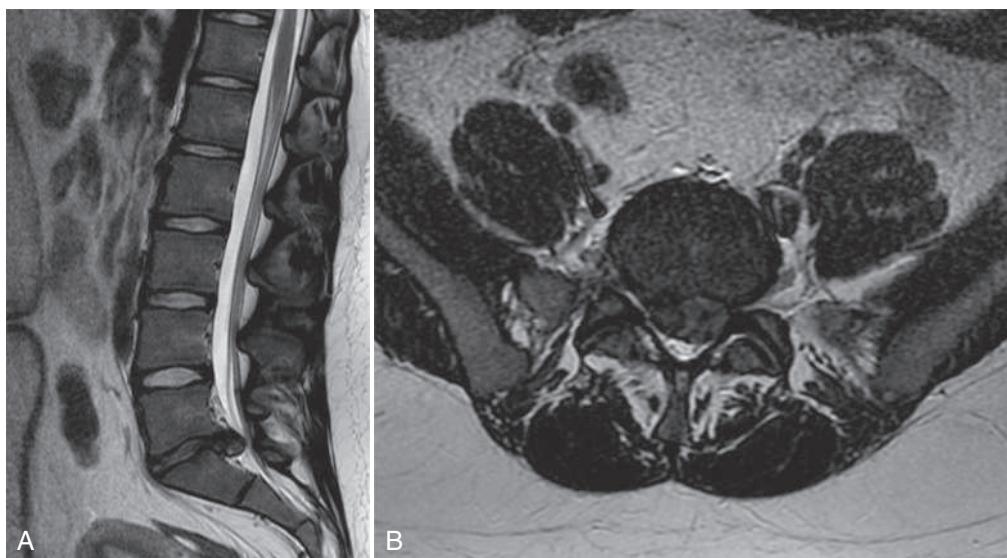


Fig. 720.15 Lumbar disk herniation. Sagittal (A) and axial T2-weighted (B) images demonstrate a disk extrusion at L5-S1 level with near-complete infilling of bilateral lateral recesses, left greater than right, and effacement of the thecal sac. (From Bossmanni T, Huisman TAGM. *Spine imaging*. In: Walters MM, Robertson RL, eds. *Pediatric Radiology: The Requisites*, 4th ed. Philadelphia: Elsevier; 2017: Fig. 9.30, p. 345.)

of the neural elements and underlying disk. Any loose fragments are removed. A bulging disk may also be opened surgically to decompress the area compressing the neural elements, although a complete discectomy is inadvisable. The surgical approach is similar in the case of a slipped vertebral apophysis, in which fragments of bone and cartilage must also be removed. This often requires a bilateral laminotomy to completely address the pathology. Patients with congenital lumbar spinal stenosis may be more likely to require surgical treatment and also may require a posterior decompression in addition to the discectomy.

The initial results are excellent in the majority of patients. Approximately 30% may have recurrent herniations and resultant symptoms of back or leg pain at longer-term follow-up. These recurrences are initially treated nonoperatively; however, repeat discectomy may be required, and if so, a significant number of patients may require a spinal arthrodesis to stabilize the damaged motion segment. A spinal fusion may also be required for instability associated with spondylolisthesis or other etiology.

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720.9 Tumors

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Back pain may be the most common presenting complaint in children who have a tumor involving the vertebral column or the spinal cord. Other associated symptoms may include weakness of the lower extremities, scoliosis, and loss of sphincter control. The majority of tumors are benign (see Chapter 550), including osteoid osteoma, osteoblastoma, aneurysmal bone cyst, and eosinophilic granuloma. Malignant tumors involving the vertebral column may be osseous, such as osteosarcoma or Ewing sarcoma. They may involve the spinal cord and sympathetic or parasympathetic nerves in cases of ganglioneuroma, ganglioneuroblastoma, and neuroblastoma. Tumors from other primary sites can also metastasize to the spine.

High-quality plain radiographs may show **vertebra plana**, or symmetric collapse of a single vertebra with preserved disk space; this is most commonly seen with eosinophilic granuloma (Fig. 720.16). Other useful imaging modalities include bone scans, which help with localization and identification of other lesions; MRI, which is helpful

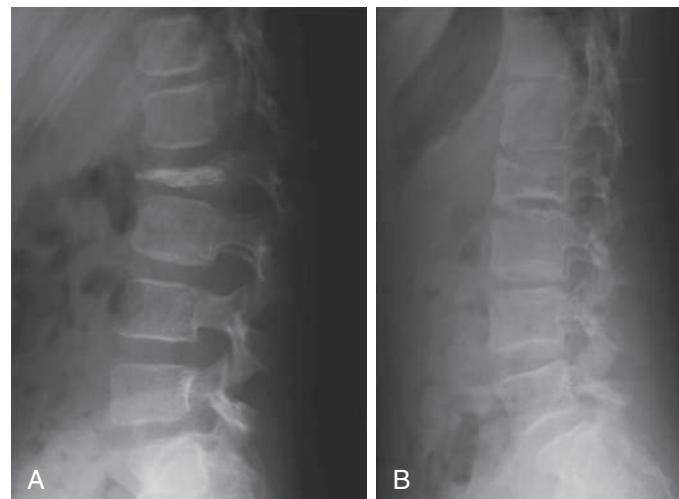


Fig. 720.16 (A) Lateral radiograph of the lumbar spine of a 6-yr-old female with a painful osteolytic lesion of the L2 vertebral body with vertebral plana deformity. CT-guided frozen section biopsy showed eosinophilic granuloma; intralesional methylprednisolone injection was performed. (B) Lateral radiograph of the lumbar spine shows complete reconstitution of the lesion 7 years after diagnosis and treatment. (From Angelini A, Mavrogenis AF, Rimondi E, et al. Current concepts for diagnosis and management of eosinophilic granuloma of bone. *J Orthop Traumatol*. 2017;18:83-90. Fig. 3.)

to identify soft tissue extension and neurologic compression; and CT, which provides excellent bony detail.

A biopsy is usually required to establish the diagnosis. Treatment of tumors of the spinal column may require a multidisciplinary approach. These cases should ideally be managed in centers with experience in the care of patients with these lesions. Many lesions are surgically treated by laminectomy, and postoperative surveillance is essential to identify cases of postlaminectomy kyphosis or other spinal deformities, which when progressive may require an instrumented spinal fusion to stabilize.

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Chapter 721

The Neck

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

721.1 Torticollis

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Torticollis, literally meaning “twisted neck,” is not a diagnosis but rather a clinical manifestation of a variety of underlying conditions (Table 721.1). Common names associated with this condition include “wry-neck” and “cock-robin” deformity. Although congenital muscular torticollis is the most common diagnosis in cases presenting at or close to the time of birth, the differential diagnosis for acquired torticollis is large. Therefore a thorough evaluation is required to identify the underlying cause.

CONGENITAL MUSCULAR TORTICOLLIS

Congenital muscular torticollis (CMT) is due to a contracture of the sternocleidomastoid (SCM) muscle, which results in a *tilting* of the head and neck *toward* the side of the contracted muscle with *rotation* of the head to the *opposite* side (Fig. 721.1). In most cases (75%), the right SCM muscle is involved, causing the patient’s face and chin to point to the left side.

CMT is thought to result from an intrauterine deformation or compression and is more common in children of primigravida mothers. CMT may be associated with the presence of a palpable mass or nodule of fibrous tissue within the substance of the SCM muscle in approximately 50% of cases (Figs. 721.2 and 721.3). Findings on muscle biopsies and MRI studies led to the hypothesis that SCM muscle injury from compression or stretch may create localized ischemia, which in turn results in fibrosis and subsequent contracture—essentially an intramuscular compartment syndrome. In rare cases, the condition can result from hereditary muscle aplasia.

Associated findings with CMT include plagiocephaly, facial asymmetry, and positional musculoskeletal deformities such as metatarsus adductus (15%) and calcaneovalgus feet. Hip dysplasia may be identified in 8–20% of affected patients. In addition to routine screening by physical examination for hip dysplasia, providers should consider obtaining either an ultrasound at 6 weeks of age or a plain radiograph of the pelvis at 4–6 months of age in children with CMT even if the physical exam is normal and there are no other risk factors for DDH.

The cornerstone of treatment for CMT is physical therapy and a home stretching program in which caregivers are instructed to gently stretch the contracted SCM by rotating the infant’s chin to the ipsilateral shoulder and simultaneously tilting the head toward the contralateral shoulder. The best results occur when treatment is started within the first 3 months of life, leading to resolution in nearly all cases. Patients who start their physical therapy later can expect a more prolonged course, and a subset will not achieve a normal range of motion. Recently, single frequency microcurrent has been used as an adjunct to physical therapy with the goal of reducing the time of treatment and also addressing the challenges of patients presenting at a later age. Botulinum toxin injections may also be considered as an adjunct, especially in resistant cases in older patients. Plagiocephaly commonly accompanies CMT, and patients may be referred to a craniofacial clinic or specialist for discussion of treatment with a cranial remolding helmet. Early restoration of motion reduces the likelihood that patients will have persistent facial asymmetry or cranial molding abnormalities.

Although firm guidelines for imaging the cervical spine have not been established, anteroposterior (AP) and lateral radiographs of the cervical spine may be obtained when the typical clinical features

associated with congenital muscular torticollis are absent or if the deformity does not respond to the stretching treatment, because torticollis in infants may also be due to **congenital vertebral anomalies**.

Surgical release of the SCM is considered in patients with *persistent deformity* after failure of conservative treatment. The muscle may be released at its insertion on the clavicle (unipolar release) or at both its origin and insertion (bipolar release). There is no agreement as to the most appropriate time for the surgical release, but surgical treatment is typically delayed until at least 18 months of age; some even suggest waiting until the child is approaching school age. Although range of motion can be improved after surgical release even during the teenage years, remodeling of facial asymmetry and plagiocephaly may be less predictable in patients older than infancy. Surgical management results in satisfactory function and acceptable cosmesis in more than 90% of patients; however, with early diagnosis and treatment, surgery should be required in only a minority of cases. Patients who have residual or untreated CMT beyond a year of age may develop secondary skeletal abnormalities such as a mild cervicothoracic scoliosis or rotational malalignment and tilting of upper and lower cervical vertebrae (especially at the atlantoaxial joint). It is presumed that such malalignment will improve with release of contracture, but in older patients, skeletal deformities may persist.

Table 721.1 Differential Diagnosis of Torticollis

CONGENITAL

Muscular torticollis
Positional deformation
Hemivertebra (cervical spine)
Unilateral atlanto-occipital fusion
Klippel-Feil syndrome
Unilateral absence of sternocleidomastoid
Pterygium colli

TRAUMA

Muscular injury (cervical muscles)
Fibromatosis coli (sternocleidomastoid tumor of infancy)
Atlanto-occipital subluxation
Atlantoaxial subluxation
C2-3 subluxation
Rotary subluxation
Fractures
Foreign body

INFLAMMATION

Cervical lymphadenitis
Retropharyngeal abscess
Cervical vertebral osteomyelitis
Grisel syndrome (nontraumatic subluxation of the atlantoaxial joint due to local inflammation)
Juvenile idiopathic arthritis
Lemierre syndrome
Upper lobe pneumonia

NEUROLOGIC

Visual disturbances (nystagmus, superior oblique or lateral rectus paresis)
Dystonic drug reactions (phenothiazines, haloperidol, metoclopramide)
Cervical cord tumor
Posterior fossa brain tumor
Syringomyelia
Wilson disease
Dystonia musculorum deformans

OTHER

Acute cervical disk calcification
Sandifer syndrome (gastroesophageal reflux, hiatal hernia)
Benign paroxysmal torticollis
Bone tumors (eosinophilic granuloma)
Soft tissue tumor
Psychogenic



Fig. 721.1 Congenital muscular torticollis. A, Torticollis secondary to a contracted left sternocleidomastoid (SCM) muscle. B, Mass in right SCM (arrow) of a newborn. Note intrauterine folding deformity of the right ear. C, Flattening of the left occipital area and left ear formation resulting from supine positioning of a child with right congenital torticollis. (From Johnson CE. Disorders of the neck. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig 8.6, p. 93.)



Fig. 721.2 Clinical presentation of a 2- x 2-cm firm, left-sided neck mass. (From Baik G, Blask A, Reilly BK. Unilateral neck mass in a neonate. J Pediatr. 2018;202:329, Fig. 1.)

OTHER CAUSES OF TORTICOLLIS

The evaluation of torticollis becomes more complex when the typical findings associated with CMT are absent, the usual clinical response is not observed, or the deformity presents at a later age. In addition to a careful history and physical examination, consultation with an ophthalmologist and neurologist will be helpful. Plain radiographs should be obtained, and MRI of the brain and cervical spine will be required in a subset of cases.

The differential diagnosis is extensive (see Table 721.1). **Neurogenic torticollis** is uncommon and results from tumors of the posterior fossa or brainstem, syringomyelia, and Arnold-Chiari malformation. In addition to the neurologic examination, MRI of the brain and cervical spine is required to establish the diagnosis. **Benign paroxysmal torticollis** of infancy is also uncommon and may be due to vestibular dysfunction. Episodes may last from minutes to days, and the side of the deformity may alternate. The condition is self-limiting, and no specific treatment is required other than ruling out other treatable causes. Torticollis may also be seen in association with diskitis or vertebral osteomyelitis; juvenile idiopathic arthritis; cervical disk calcification; visual problems, such as congenital nystagmus or paresis of the superior oblique or lateral rectus muscle; benign or malignant bone tumors; and in cerebral palsy and chronic gastroesophageal reflux from a hiatal hernia (**Sandifer syndrome**).

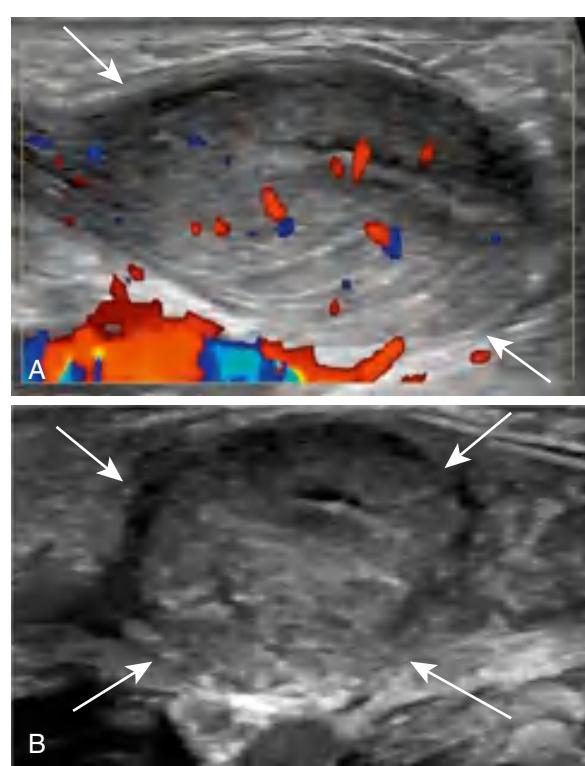


Fig. 721.3 Sonographic image of the symptomatic left neck in a 3-wk-old neonate with fibromatosis colli of the left sternocleidomastoid muscle. A, Longitudinal image of the sternocleidomastoid muscle showing enlargement with a fusiform configuration and masslike focus within the expanded segment of the muscle (arrows). The echotexture of the mass is mildly heterogeneous and echogenic compared with the normal muscle on the contralateral side. Color flow is preserved within the mass. B, The mass has a more rounded configuration on the transverse ultrasound image (arrows). (From Baik G, Blask A, Reilly BK. Unilateral neck mass in a neonate. J Pediatr. 2018;202:329, Fig. 2.)

ATLANTOAXIAL ROTATORY DISPLACEMENT

Atlantoaxial rotatory displacement (AARD) represents a spectrum of pathology involving axial alignment (rotational) and motion between C1 and C2. The vertebrae may be partially displaced (subluxated) or completely displaced (dislocated) in the neutral or resting position with head facing forward. Motion between the vertebrae may

be normal (reducible with full range of motion), "sticky" (partially reducible with loss of motion), or fixed (irreducible with no motion between C1 and C2). Loss of motion at the C1-C2 joint results in 50% loss of cervical rotation. Prompt diagnosis and treatment are essential as the malalignment may become irreducible after several weeks. If the displacement persists, the facet of C2 will become deformed (resulting in increased forward slope), which increases the risk of C1 facet sliding off of the C2 facet leading to relapse of deformity.

AARD may complicate infection or inflammation of the tissues of the upper airway, neck, or pharynx (**Grisel syndrome**), minor traumatic injuries, and surgical procedures in the oropharynx, ear, or nose. The diagnosis is most often made clinically, with the SCM muscle on the *contralateral* side (away from the head tilt) in spasm and prominent. Additionally, patients with AARD often have pain at rest and with head manipulation, features not seen with CMT. Plain radiographs are difficult to interpret given the head tilt, and AARD is best appreciated on a dynamic rotational CT scan, in which axial images are obtained through the upper cervical spine with the head at neutral and rotated maximally toward both the right and the left. The patient must be relaxed and comfortable for images to be successfully obtained. MRI may demonstrate edema or inflammation of the supporting ligaments. Clinicians may choose to treat a patient empirically if the history and clinical findings are characteristic, reserving advanced imaging for patients who have not responded clinically. If the patient is seen within a few days of the onset of symptoms, a trial of analgesics and a soft collar may be attempted. Patients with symptoms that persist or have been present for more than a week are often admitted to the hospital for analgesia, muscle relaxants, and a period of soft cervical traction. If this fails to reduce the displacement, halo traction may be attempted. If the joint can be reduced, patients are typically immobilized for at least 6 weeks in a halo vest. The treatment course is more challenging and outcomes less favorable for patients presenting more than 4 weeks after symptom onset. In such cases traction is typically employed to reduce the joint and then a halo vest used for up to 3-4 months to maintain the reduction. Some have used manipulation under anesthesia to obtain reduction before manipulation. The longer period of immobilization in these chronic cases allows for remodeling of the C2 facet, therefore reducing the risks of relapse after treatment. For those who fail these nonoperative treatment strategies, the most common treatment is a C1-C2 arthrodesis. A less common approach has been to perform an open reduction of the joint followed by either immobilization or by surgical fusion.

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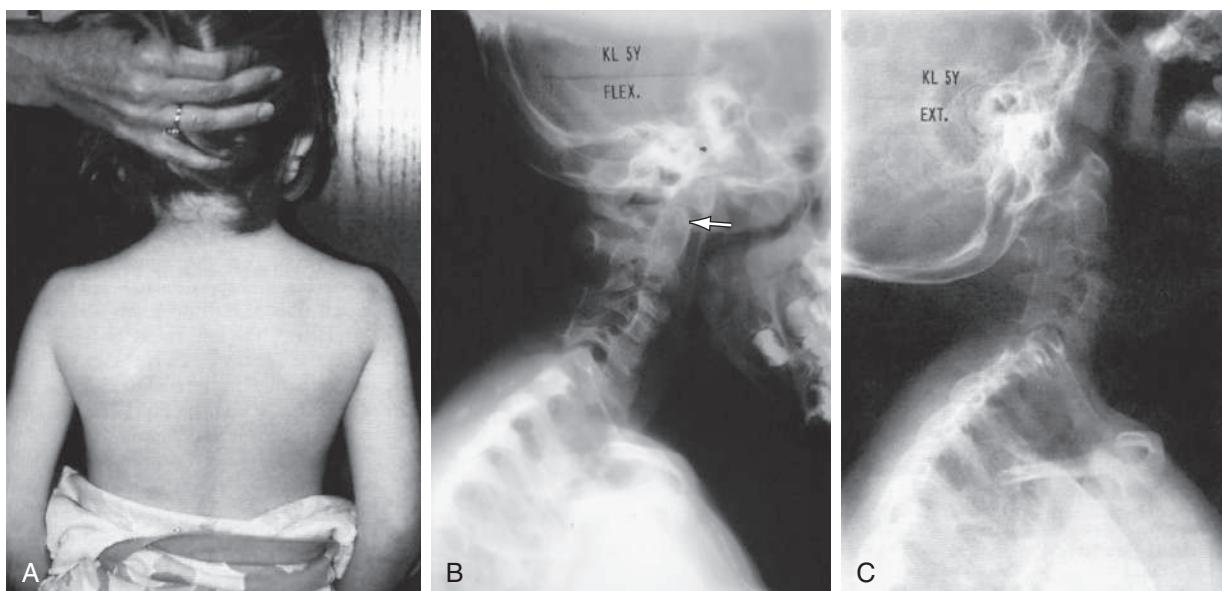


Fig. 721.4 Clinical picture of a 5-yr-old with Klippel-Feil syndrome. A, Note short neck and low hairline. B and C, Radiographs of the cervical spine (B, flexion; C, extension) demonstrate congenital fusion and evidence of spinal instability (arrow). (From Drummond DS. Pediatric cervical instability. In: Weisel SE, Boden DS, Wisnecki RI, eds. Seminars in Spine Surgery. Philadelphia: WB Saunders; 1996:292-309.)

721.2 Klippel-Feil Syndrome

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Klippel-Feil syndrome (KFS) includes the classic triad of a low posterior hairline, short neck, and decreased cervical range of motion (Fig. 721.4). However, these clinical findings are present in <50% of patients with KFS. Limited cervical motion may be the most common finding, present in 64.5% of patients, whereas only 9.7% of patients had all three findings. Patients have a congenital fusion (**failure of segmentation**) of one or more cervical motion segments at the craniocervical junction and/or in the subaxial spine and often have additional associated congenital anomalies of the cervical spine and other organ systems.

Additional findings in the cervical spine include occipitocervical synostosis, odontoid abnormalities, basilar invagination (proximal migration of the C2 vertebra above the foramen magnum), and Chiari malformation. Other associations include **Sprengel's deformity** (congenital elevation of the scapula), congenital scoliosis, genitourinary anomalies (25–35%), sensorineural hearing loss (5%), and congenital heart disease (5–10%). Renal abnormalities include double collecting systems, renal aplasia, and horseshoe kidney. The cervical spine anomalies seen in patients with KFS may also be seen with Goldenhar syndrome, Mohr syndrome, VACTERL syndrome, and fetal alcohol syndrome. Clinical problems are more common in adults and include pain or neurologic symptoms from spinal instability or stenosis. Although the incidence has been estimated at 1 in 40,000–42,000 births, many patients with this condition are undiagnosed.

ETIOLOGY AND CLASSIFICATION

Most cases are sporadic, but four genetic forms have been described, two of which are autosomal dominant and two are autosomal recessive. A number of chromosomal abnormalities have also been associated with KFS. Pathogenic variants have been reported in the mesenchymal homeobox 1 gene (*MEOX1*, regulates segmentation of vertebrae), the growth differentiating factor 3 or 6 genes (*GDF*), and the myosin 18 (*MYO18B*) gene.

One classification system is the most practical and has three types, namely a single fused segment (I), multiple noncontiguous fusions (II), and multiple contiguous fused segments (III). Patients with type I tend to have axial pain, whereas those with types II/III are more likely to have neurologic symptoms.

CLINICAL PRESENTATION

KFS is present at birth but does not usually become clinically apparent until the second or third decades. Patients at this point present with pain, loss of motion, or neurologic symptoms. Pain is extremely common by adulthood and may be referred to the neck, occiput, and shoulders/upper back. The source of discomfort may be musculoskeletal and/or neurologic. The pain is greater in patients with more extensive involvement. Headache, dizziness, and fatigue have also been reported. Given that the same physiologic stresses are applied to a smaller number of mobile spinal segments, patients are at risk for the development of hypermobility and often instability, especially at motion segments adjacent to the fused vertebrae. Weakness or clumsiness consistent with **myelopathy** may be the presenting symptoms.

PHYSICAL EXAMINATION

A comprehensive musculoskeletal and neurologic examination is required, given associated anomalies in the musculoskeletal and visceral systems. **Scoliosis** is present in more than 50% of patients with KFS, and congenital anomalies may be identified in other regions of the spine as well. The neurologic exam focuses on identifying any signs of radiculopathy or myelopathy. Spinal cord compression, or myelopathy, may result from stenosis or instability. A physical exam will demonstrate upper motor neuron signs such as hyperreflexia, Hoffman's sign, Babinski's sign, and sustained clonus, with more than three beats considered pathologic. Nerve root compression, or radiculopathy, may be due to stenosis and is identified by weakness or decreased sensation in the muscles or dermatomes served by a particular nerve root.

RADIOLOGIC INVESTIGATION

Initial radiologic evaluation should include an AP, lateral, and oblique view of the cervical spine. The characteristic finding is a congenital fusion of two or more vertebrae resulting from a failure of segmentation; however, multiple vertebrae may be involved. Because congenital anomalies may exist in more than one region of the spine, radiographs of the thoracic and lumbosacral spine should be routinely obtained. Flexion-extension lateral views of the cervical spine may help to identify segments with excessive motion. Referral to an orthopedist is appropriate once the diagnosis is established. Patients with this condition usually undergo CT and MRI of the spine to accurately characterize the bony anomalies and also identify any coexisting neural pathology. A renal ultrasound is routinely obtained to identify associated anomalies (e.g., duplicated collecting system, absence of a kidney, horseshoe kidney). Additional imaging, such as echocardiogram, may identify cardiovascular anomalies, mainly septal defects.

Audiologic evaluation is indicated for patients diagnosed with KFS; hearing impairment may be identified in up to one third of affected patients.

TREATMENT

The three patterns commonly associated with instability include (1) C2/C3 fusion with occipitocervical synostosis, (2) extensive fusion over multiple levels with an abnormal occipitocervical junction, and (3) two fused segments separated by an open joint space.

Pain may often be controlled by activity restriction, intermittent immobilization, or other nonoperative modalities. Patients who are chronically symptomatic, have instability with positive neurologic symptoms or exam findings, or are thought to be at increased risk for neurologic deterioration are candidates for surgical treatment. Operative interventions include decompression of nerve roots or the spinal cord itself and/or spinal fusion to address cervical spinal instability.

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Table 721.2 Causes of Pediatric Cervical Instability	
CAUSES	SUBTYPES
Congenital	Cranio-occipital defects (occipital vertebrae, basilar impression, occipital dysplasias, condylar hypoplasia, occipitalized atlas) Atlantoaxial defects (aplasia of atlas arch, aplasia of odontoid process) Subaxial anomalies (failure of segmentation and/or fusion, spina bifida, spondylolisthesis) Syndromic disorders (e.g., Down syndrome, Klippel-Feil syndrome, 22q11.2 deletion syndrome, Larsen syndrome, Marfan syndrome, Ehlers-Danlos syndrome)
Acquired	Trauma Infection (pyogenic/granulomatous) Tumor (including neurofibromatosis) Inflammatory conditions (e.g., juvenile idiopathic arthritis) Osteochondrodysplasias (e.g., achondroplasia, diastrophic dysplasia, metatropic dysplasia, spondyloepiphyseal dysplasia) Storage disorders (e.g., mucopolysaccharidoses) Metabolic disorders (rickets) Miscellaneous (including osteogenesis imperfecta, after surgery)

721.3 Cervical Anomalies and Instabilities

R. Justin Mistovich, Keith D. Baldwin, and David A. Spiegel

Anomalies of the craniocervical junction or lower cervical spine may be seen in isolation or in association with other conditions. These include genetic syndromes, skeletal dysplasias, connective tissue disorders, and metabolic disorders. These anomalies may be congenital or developmental. Although most anomalies remain asymptomatic and undiagnosed, a subset will place the patient at risk of neurologic injury as a result of instability or spinal canal stenosis. The most frequently encountered causes of cervical spine instability in children can be categorized etiologically (Table 721.2). Patients with conditions that have known associations involving the cervical spine should have a complete evaluation, including history, physical examination, and initial radiographic examination. Lateral radiographs in flexion and extension may be helpful to evaluate instability, and advanced imaging such as CT or MRI may be required to further characterize any abnormalities noted on plain radiographs.

Patients may complain of neck pain or neurologic symptoms. Radicular symptoms include pain, weakness, and numbness within the distribution of a nerve root. Myelopathic symptoms include generalized weakness, gait disturbance, increased fatigue with ambulation, upper extremity clumsiness, and abnormalities in bowel or bladder function. Other symptoms such as headaches, dizziness, or vertigo have also been described. Physical exam findings may include restricted cervical mobility, cervical tenderness or spasm, and neurologic abnormalities.

Although the upper cervical spine has limited flexion and extension, roughly 50% of cervical rotation occurs at the atlantoaxial (C1-2) joint. The main constraints to motion in the upper cervical spine are soft tissue (ligaments and joint capsules) rather than osseous. Excessive motion or instability may result in a compressive injury to the brainstem or spinal cord. Anomalies at the craniocervical junction include congenital fusion of the occiput to C1 (**occipitalization** of the atlas), basilar impression and invagination (proximal migration of the C2 vertebra as the result of softening of the bones and with normal bones, respectively), and accessory vertebrae. Aplasia or hypoplasia of the atlas or the axis may result in atlantoaxial instability.

OS ODONTOIDEUM

Os odontoideum is the most common anomaly of the odontoid, or dens, and radiographically appears as an oval-shaped, well-corticated bony ossicle that is positioned cephalad to the body of the axis. There is a discontinuity, and the upper portion of the dens moves with the ring of C1, narrowing the space available for the spinal cord and placing it at risk for injury. The body of the dens is mesenchymal in origin and originates from the first cervical vertebra. Subsequent separation allows it to then fuse with the C2 vertebra. It is formed by two separate ossification centers, one on either side of the midline that eventually fuse and are visible at birth. The os odontoideum may be in a normal anatomic position (orthotopic) or adjacent to the occipital bone (dystopic). Although the etiology remains unclear, both traumatic (nonunion of a fracture, repetitive shear stresses from hypermobility on growing cartilage) and developmental (failure of fusion of the ossification centers) theories have been proposed.

Symptoms may include pain and/or neurologic dysfunction. Myelopathy may develop from neural stretch, ischemia, or bony impingement, whereas vertebral artery findings may result from ischemia due to stretching or thrombosis of the vertebral arteries. Neurologic examination may reveal a combination of both upper and lower motor neuron signs. Some patients are completely asymptomatic with the anomaly noted incidentally on a lateral cervical spine radiograph.

The radiographic evaluation begins with AP, lateral, and open mouth odontoid views, which may be supplemented by flexion and extension lateral radiographs. CT provides the best bony detail and is useful in defining each anomaly. MRI, including dynamic images in flexion and extension, is best for evaluating neurologic impingement.

Patients who are asymptomatic with no instability may be managed by observation with serial radiographs, activity restriction, and taking special precautions if they require intubation/general anesthesia. Those with neurologic symptoms and instability require surgical stabilization by an instrumented posterior arthrodesis between C1 and C2.

Down Syndrome

Ligamentous hyperlaxity is a characteristic feature of Down syndrome and may result in hypermobility or instability at the occipitatoatlantal or the atlantoaxial joints in 4–30% of patients (see Chapter 57). These patients may also have coexisting congenital or developmental anomalies of the cervical spine, such as occipitalization of the atlas, atlantal arch hypoplasia, basilar invagination, and os odontoideum.

Although the natural history of this spectrum of pathology remains unknown, a small subset of patients will develop instability with neurologic dysfunction. The clinical diagnosis of neurologic dysfunction may be challenging because patients often present with subtle findings such as decreased exercise tolerance, tripping/falling, or other gait abnormalities. The challenge lies in the early identification of such cases, especially in patients who plan to participate in activities with increased risk of trauma to the head or neck such as tumbling or other sports.

All patients with Down syndrome require screening by history and physical examination at regular intervals. The guidelines for health supervision for children with Down syndrome suggest that routine radiographic screening is not indicated in asymptomatic patients and that a lateral radiograph in neutral alignment should be obtained for all patients with symptoms of possible atlantoaxial instability (neck pain, radicular pain, weakness, spasticity/change in tone, gait difficulties, hyperreflexia, or change in bowel or bladder function). Dynamic images are suggested when abnormalities

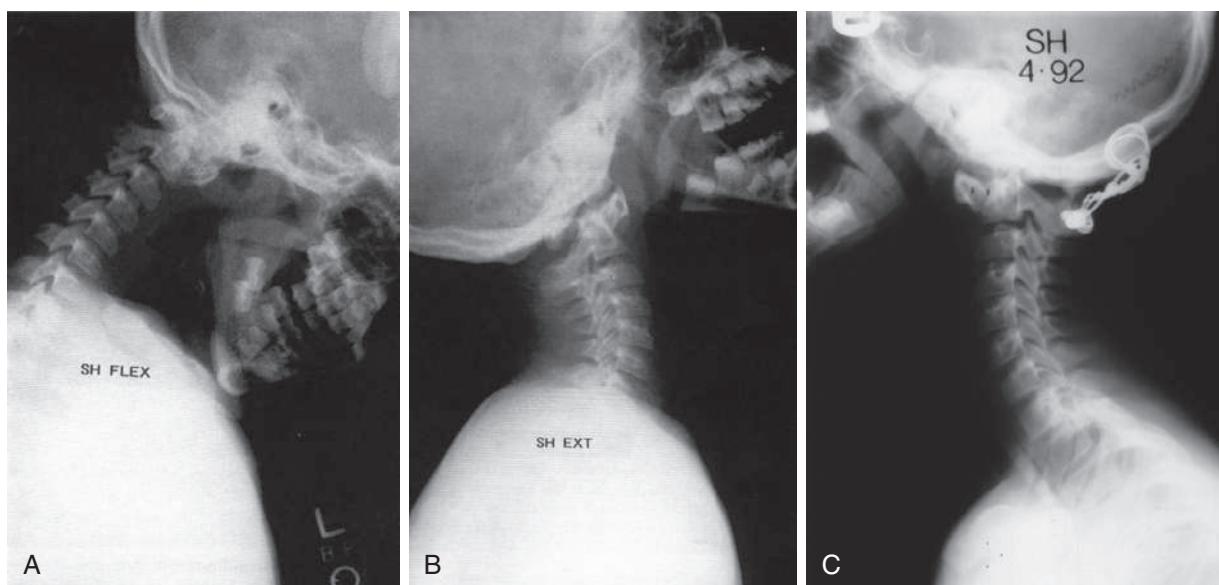


Fig. 721.5 Flexion (A) and extension (B) radiographs of a case of Down syndrome demonstrating atlanto-occipital hypermobility and subluxation. C, Instability and symptoms were relieved by an occipitoaxial arthrodesis.



Fig. 721.6 Radiographs of the cervical spine in a child with 22q11.2 deletion syndrome showing evidence of platybasia, occipitocervical, and atlantoaxial instability. A, Neutral radiograph. B, Flexion. C, Extension. (From Drummond DS. Pediatric cervical instability. In: Weisel SE, Boden DS, Wisneki RL, eds. *Seminars in Spine Surgery*. Philadelphia: WB Saunders; 1996:292–309.)

are present on the initial lateral radiograph. Although variations in practice patterns likely exist and recommendations may vary between states, radiographic screening is required before participation in the Special Olympics. Patients with coexisting os odontoideum are candidates for routine radiographic surveillance because they are at greater risk for progression of displacement and neurologic injury.

Plain radiographs are ideally obtained in children older than 3 years unless clinical findings mandate earlier evaluation, consisting of an AP and lateral in neutral alignment, usually supplemented by a lateral view in flexion and extension. The atlanto-dens interval (ADI) is used to evaluate the relationship between C1 and C2 (atlantoaxial joint) and is measured as the space between the dens and the anterior ring of C1 on lateral radiographs in neutral, flexion, and extension (Fig. 721.5). Although the ADI should be 3 mm or less in the population without Down syndrome, a normal ADI in children with Down syndrome is <4.5 mm. Hypermobility is diagnosed as an ADI between 6 and 10 mm, whereas an ADI >10 mm represents frank instability and carries greater risk of neurologic injury. Evaluating the space available for the spinal cord is also important, and a measurement of ≤14 mm between the posterior odontoid and posterior arch is felt to be abnormal. Progression from hypermobility to instability on surveillance radiographs is uncommon. In one series of patients with Down syndrome screened routinely, an ADI of ≥6 mm was identified in 4.4%, and 1.6% were noted to progress to hypermobility/instability over 4 years. MRI in flexion and extension is indicated to evaluate for impingement and/or neurologic injury in patients with appropriate clinical symptoms or findings and/or those with radiographic instability, and an increase in signal intensity within the spinal cord at the level of excessive motion is diagnostic of neurologic injury.

Although hypermobility at the occipitoatlantal joint is present in >50% of children with Down syndrome, most patients do not develop instability or neurologic symptoms. The relationships at this articulation are difficult to measure reliably on plain radiographs. An MRI in flexion and extension is required to evaluate any questionable radiographic findings, especially in the presence of clinical symptoms. Involvement of the subaxial spine is less common and is typically encountered in the adult population of patients with Down syndrome. Degenerative changes or instability may result in pain, radiculopathy, and/or myelopathy.

Specific treatment recommendations have not been standardized, but patients diagnosed with hypermobility may be restricted from participation in contact sports and other activities that increase the risk of trauma to the cervical spine. Patients with C1-2 instability

with or without neurologic findings are candidates for an atlantoaxial fusion.

22Q11.2 Deletion Syndrome

The chromosome deletion of 22q11.2 is a common genetic syndrome, with an overall prevalence of 1 in 5,950 births and encompasses a wide spectrum of abnormalities. There are characteristic facial features, cleft palate, and cardiac anomalies. Cervical spine anomalies are also common. At least one developmental variation of the occiput or cervical spine is noted in all patients. The occipital variations observed include **platybasia**, an abnormal flattening of the base of the skull, and **basilar impression**. Variations in anatomy of C1 include dysmorphic shape, an open posterior arch, and occipitalization, while axis variations include a dysmorphic dens and “C2 swoosh” (upswept lamina and posterior elements). A range of cervical vertebral fusions is noted in these patients, the most common being at the C2-3 level. Increased segmental motion is commonly observed, but symptomatic instability is quite uncommon. With frequent occurrence of upper cervical spine anomalies in patients with 22q11.2 deletion syndrome (Fig. 721.6), advanced imaging of the upper cervical spine is suggested to characterize the anomalies. Regular follow-up is required as a small subset of patients may develop instability. A flexion-extension MRI of the cervical spine may be considered for evaluation of symptomatic patients to rule out instability and/or neurologic injury.

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Chapter 722

The Upper Limb

Robert B. Carrigan

SHOULDER

The shoulder is a ball-and-socket joint that is similar to the hip; however, there are several anatomic differences between the two. The shoulder is a very shallow ball-and-socket joint compared to the hip and is more prone to dislocation than the hip. In addition, shoulder

range of motion (ROM) is much greater than that of the hip. This is due to the size of the humeral head relative to the glenoid and the presence of scapulothoracic motion. The shoulder positions the hand along the surface of a theoretical sphere in space, with its center at the glenohumeral joint.

Sprengel Deformity

Sprengel deformity, or congenital elevation of the scapula, is a disorder of development that involves a high scapula and limited scapulothoracic motion. The scapula originates in early embryogenesis at a level posterior to the fourth cervical vertebra. It descends during development to below the seventh cervical vertebra. Failure of this descent, either unilateral or bilateral, is the Sprengel deformity. The severity of the deformity depends on the location of the scapula and associated anomalies. The scapula in mild cases is simply rotated, with a palpable or visible bump corresponding to the superomedial corner of the scapula. Function is generally good. In moderate cases, the scapula is higher on the neck and connected to the spine with an abnormal omovertebral ligamentous or bony connection. Shoulder motion, particularly abduction, is limited. In severe cases, the scapula is small and positioned on the posterior neck. The neck may be webbed. Most patients with Sprengel deformity have associated anomalies of the musculoskeletal system, especially in the spine (Klippel-Feil syndrome), making spinal evaluation important.

Treatment

In mild cases, treatment is generally unnecessary. A prominent and unsightly superomedial corner of the scapula can be excised. In more severe cases, surgical repositioning of the scapula with rebalancing of parascapular muscles can significantly improve both function and appearance.

Congenital Pseudarthrosis of the Clavicle

The clavicle is a tubular S-shaped bone that articulates with the sternum and acromion. It acts as a strut to keep the shoulder from protracting forward. Congenital pseudarthrosis of the clavicle is a failure of the two primary ossification centers of the clavicle to fuse during embryogenesis (Fig. 722.1). The condition presents exclusively on the right side and may be confused for an acute clavicle fracture sustained during birth. A thorough history and physical exam will help to distinguish between the two conditions. Although both a birth-related clavicle fracture and a congenital pseudarthrosis will present with a bump or prominence over the mid-clavicle, a birth-related clavicle fracture will be tender to palpation on exam. The parents may also report that the child is fussy with feeding and changing. Congenital pseudarthrosis of the clavicle will be painless on exam. Radiographically the congenital pseudarthrosis clavicle will have two rounded edges at the midportion with signs of hypertrophy.



Fig. 722.1 Radiograph of congenital pseudarthrosis of the clavicle.

Treatment

There is not a clear consensus regarding treatment of congenital pseudarthrosis of the clavicle. Surgery is indicated for patients with symptoms of **thoracic outlet syndrome** (impingement of the clavicle on the brachial plexus and subclavian vessels). However, most patients are asymptomatic with few functional limitations and do not require surgical repair. Surgical treatment may be considered for patients with unacceptable cosmetic deformity, pain, or functional deficits.

The operative treatment of congenital pseudarthrosis of the clavicle consists of opening the pseudarthrosis site, preserving the periosteum, debriding the hypertrophic ends, bone grafting, and stabilization.

ELBOW

The elbow is the most congruent joint in the body. The stability of the elbow is imparted via this bony congruity and through the medial and radial collateral ligaments. Where the shoulder positions the hand along the surface of a theoretical sphere, the elbow positions the hand within that sphere. The elbow allows extension and flexion through the ulnohumeral articulation and pronation and supination through the radiocapitellar articulation.

Panner Disease and Osteochondritis of the Capitellum

Panner disease is a disruption of the blood flow to the subchondral bone and articular cartilage of the capitellum (Fig. 722.2). It typically occurs in males between the ages of 5 and 13 years. Presenting symptoms include lateral elbow pain, loss of motion, and, in advanced cases, mechanical symptoms of the elbow (loose bodies).

The mechanism of injury can be impaction or overloading of the joint, as seen with sports such as gymnastics and baseball. It can also be idiopathic. Radiographs of the elbow may be normal or may show a small lucency within the subchondral bone of the capitellum. MRI is the study of choice to evaluate a suspected capitellar lesion. MRI can demonstrate the extent of the involvement in the subchondral bone and the integrity of the cartilage of the articular surface.

Treatment

Treatment is typically conservative. Rest, activity modification, and patient education are initial treatment options. In cases in which the articular cartilage fragments and loose bodies form, arthroscopy of the elbow is warranted to remove the loose bodies. When the cartilage defect in the capitellum is large and symptomatic, procedures for restoration of the articular cartilage may be considered. These procedures include drilling of the subchondral bone (microfracture) to promote scar cartilage and osteochondral autograft transplantation (OATS).

Radial Longitudinal Deficiency

Radial longitudinal deficiency of the forearm comprises a spectrum of conditions and diseases that have resulted in hypoplasia or absence of the radius (Table 722.1). Clinical characteristics consist of a small, shortened limb with the hand and wrist in excessive radial deviation. Partial or complete absence of the radial structures of the forearm and hand are observed (Fig. 722.3).

Radial longitudinal deficiency can range in severity from mild to severe and has been classified into four types according to Bayne and Klug (Table 722.2). Radial longitudinal deficiency can be associated with other syndromes such as **Holt-Oram** and **Fanconi anemia**. Complete and thorough workup of these associated conditions is important for the long-term health of the child.

Treatment

The goals for the treatment of radial longitudinal deficiency include centralizing the hand and wrist on the forearm, balancing the wrist, and maintaining appropriate thumb and digital motion. Shortly after

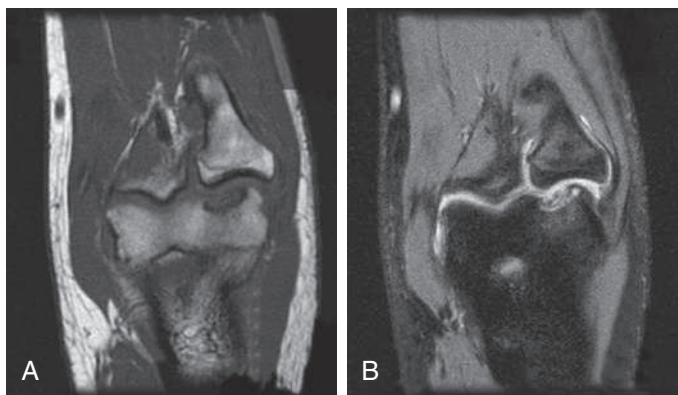


Fig. 722.2 T1 (A) and T2 (B) coronal MRI images of the elbow depicting Panner disease of the elbow.

Table 722.1 Syndromes Commonly Associated with Radial Deficiency

SYNDROME	CHARACTERISTICS
Holt-Oram syndrome	Heart defects, most commonly atrial septal defects Absent thumb or long finger-like thumb
Thrombocytopenia-absent radius syndrome	Thrombocytopenia present at birth but improves over time Thumbs present, radii absent
VACTERL association	Vertebral abnormalities, anal atresia, cardiac abnormalities, tracheoesophageal fistula, esophageal atresia, renal defects, radial dysplasia, lower limb abnormalities
Fanconi anemia	Aplastic anemia does not present at birth, develops about 6yr of age; fatal without bone marrow transplant Chromosomal breakage challenge test and genetic testing available for early diagnosis Thumb hypoplasia but present

From Trumble T, Budoff J, Cornwall R, eds. *Core Knowledge in Orthopedics: Hand, Elbow, Shoulder*. Philadelphia: Elsevier; 2005:425.

birth, stretching and splinting of the wrist and hand should be started to elongate the contracted radial soft tissues.

Surgery for correction of the wrist deformity is focused on addressing the tight structures and varies by age and level of involvement. The classic surgical technique for children with good elbow motion is centralization of the wrist on the forearm, which is often associated with recurrence of the deformity. When considering a centralization procedure, the preoperative plan begins with careful examination of the patient; considerations regarding thumb and elbow function must be made before surgery. The surgery typically occurs when the child is 1 year of age. Correction of the radial deviation as well as centralization of the wrist can be accomplished with a variety of different surgical techniques. These techniques include open release, capsular reefing, and tendon rebalancing. External fixation techniques and free tissue transfers also have been described.

Nursemaid's Elbow

Nursemaid's elbow is a subluxation and interposition of the annular ligament of the elbow. It is often confused for a subluxation or

dislocation of the radial head. The proximal end of the radius, or radial head, is anchored to the proximal ulna by the annular ligament. It wraps around like a leash from the ulna, around the radial head, and back to the ulna. If the radius is pulled distally, the annular ligament can slip proximally off the radial head and into the joint between the radial head and the humerus (Fig. 722.4). The injury is typically produced when a longitudinal traction force is applied to the arm, such as when a falling child is caught by the hand, or when a child is pulled by the hand. The injury usually occurs in toddlers and rarely occurs in children older than 5 years of age. Subluxation of the annular ligament produces immediate pain and limitation of supination. Flexion and extension of the elbow are not limited. Swelling is generally absent. The diagnosis is made by history and physical examination because radiographs are typically normal.

Treatment

The annular ligament is reduced by rotating the forearm into supination while holding pressure over the radial head. A palpable click or clunk can be felt. The child recovers active supination and usually has relief of discomfort. Sometimes pain may persist after reduction maneuvers. Immobilization is not required, but recurrence can happen. Parents should avoid activities that apply traction to the elbows. Parents can learn reduction maneuvers for recurrent episodes to avoid trips to the emergency department or pediatrician's office. Recurrence beyond 5 years of age is rare.

WRIST

The wrist is composed of the two forearm bones (radius and ulna) as well as the eight carpal bones. The wrist allows flexion, extension, and radial and ulnar deviation through the radiocarpal and midcarpal articulations. Pronation and supination occur at the wrist through the distal radial ulnar joint (DRUJ). The wrist is a complex joint with numerous ligamentous and soft tissue attachments. It has complex kinematics that allows for its generous ROM, but when these kinematics are altered, significant dysfunction can occur.

Madelung Deformity

Madelung deformity is a deformity of the wrist that is characterized as radial and palmar angulations of the distal aspect of the radius (Fig. 722.5). Growth arrest of the palmar and ulnar aspect of the distal radial physis is the underlying cause of this deformity. Bony physical lesions and an abnormal radiolunate ligament (**Vicker's ligament**) have been implicated. The deformity can be bilateral and affects females more than males.

Treatment

Treatment of Madelung deformity is typically observation. Mild deformities can be observed until skeletal maturity. Moderate to severe deformities that either are painful or limit function may be candidates for surgical intervention. Surgical treatment for Madelung deformity is often motivated by appearance. Patients and their families may be concerned about the palmar angulation of the wrist and the resulting prominent distal ulna.

There are a multitude of surgical options for treating Madelung deformity. For the skeletally immature patient, resection of the tethering soft tissue (Vicker's ligament) and physiolysis (fat grafting of any bony lesion seen within the physis) is often the first option. When Madelung deformity is encountered in skeletally mature patients, an osteotomy may be considered. Dorsal closing wedge, dome, and ulnar shortening osteotomies may be used alone or in combination to achieve the desired result.

Long-term considerations of Madelung deformity concern the incongruity of the DRUJ and resulting premature DRUJ arthritis.

Gymnast's Wrist

Gymnast's wrist refers to the changes observed in the physis of the distal radius in the setting of repetitive stress associated with gymnastics

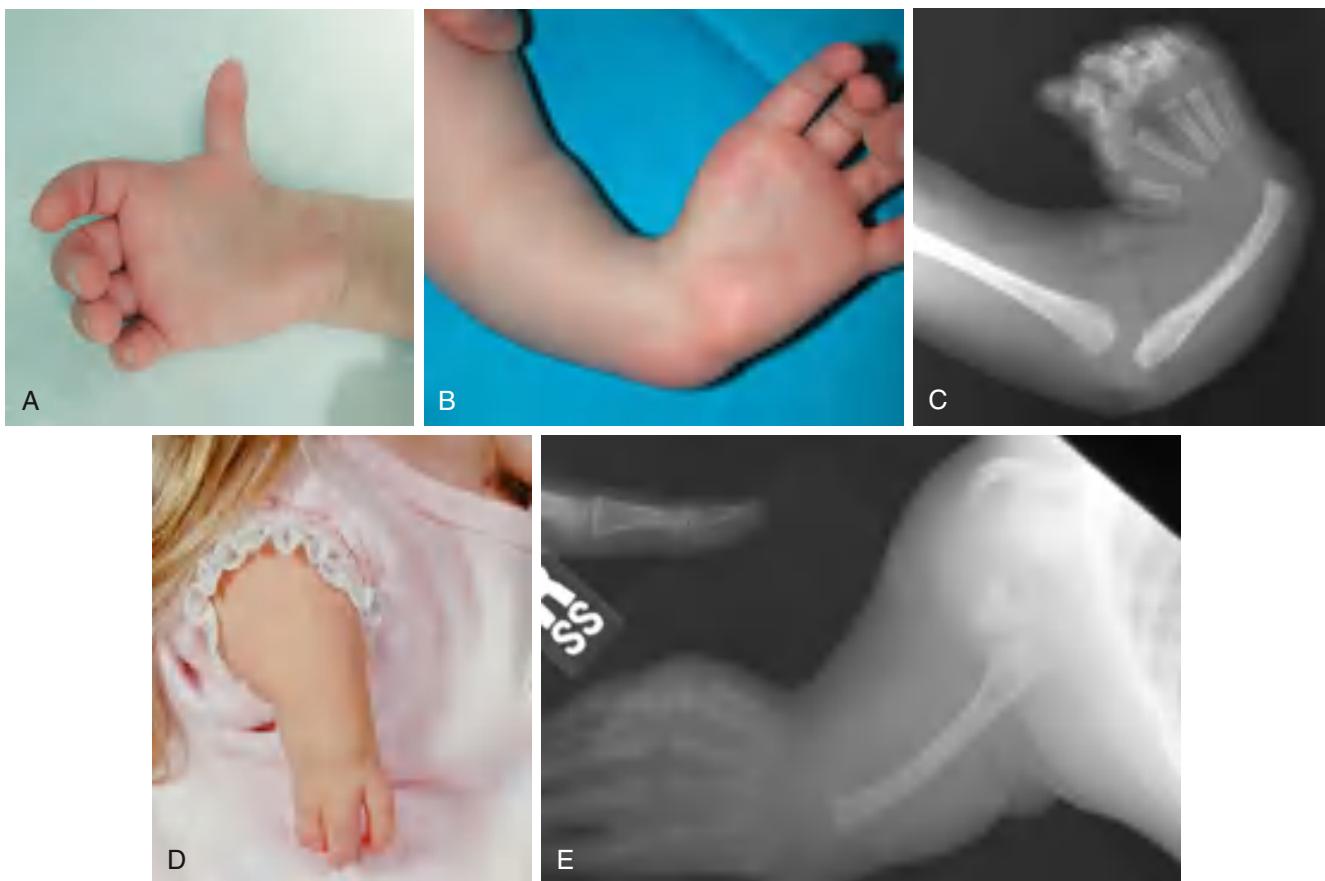


Fig. 722.3 Spectrum of phenotypes of radial dysplasia. A, Type 1 radius with a hypoplastic thumb. B, Type IV radius with an absent thumb. C, Radiograph of a type IV radius. D and E, Phocomelic radial deficiency. (From Oishi S, Stutz C, Lake A. Disorders of the upper extremity. In: Herring JA, ed. Tachdjian's Pediatric Orthopaedics, 6th ed. Philadelphia: Elsevier; 2022: Fig. 12.72, p. 337.)

Table 722.2 Modified Classification of Radial Longitudinal Deficiency

TYPE	THUMB	CARPUS	DISTAL RADIUS	PROXIMAL RADIUS
N	Hypoplastic or absent	Normal	Normal	Normal
0	Hypoplastic or absent	Absence, hypoplasia, or coalition	Normal	Normal, radioulnar synostosis, or congenital dislocation of the radial head
1	Hypoplastic or absent	Absence, hypoplasia, or coalition	>2 mm shorter than the ulna	Normal, radioulnar synostosis, or congenital dislocation of the radial head
2	Hypoplastic or absent	Absence, hypoplasia, or coalition	Hypoplasia	Hypoplasia
3	Hypoplastic or absent	Absence, hypoplasia, or coalition	Physis absent	Variable hypoplasia
4	Hypoplastic or absent	Absence, hypoplasia, or coalition	Absent	Absent

From James MA, McCarroll HR Jr, Manske PR. The spectrum of radial longitudinal deficiency: a modified classification. *J Hand Surg Am*. 1999;24:1145–1155.

(Fig. 722.6). Symptoms include pain with weight bearing, swelling, and loss of motion (mainly wrist extension). The pain is typically mild at first and worsens with time and increased activity. Children will have pain over the distal radial physis on palpation. The child should also be examined for coexisting wrist pathology including DRUJ instability and triangular fibrocartilage complex (TFCC) tears. Radiographs are often normal but may show chronic changes in the distal radial physis, including widening, sclerosis, and partial physeal arrest. Ulnar positive variance may also be observed because of partial growth arrest of the radius. MRI may be useful to examine the extent of physeal involvement as well as TFCC pathology.

Treatment

Treatment of gymnast's wrist begins with rest. Typically, the child is prohibited from weight-bearing activities for a period of 6 weeks or until symptoms resolve. The child is slowly progressed back to their routine. If symptoms return during the recovery phase, rest is reinitiated. It is not uncommon for relapses to occur when returning to competition. This may be difficult for the child and parents to understand, as gymnasts and gymnast's families are often very motivated to continue their sport. Use of braces, such as Tiger Paws, may help limit the amount of force transmitted to the wrist and in turn help with injury prevention.

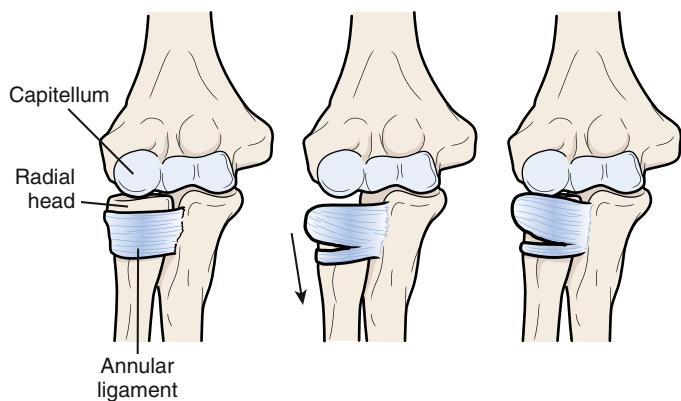


Fig. 722.4 Nursemaid's elbow. Illustration depicting subluxation of the radial head inferior to the annular ligament, with interposition of the ligament to the radiocapitellar joint space. This entity is sometimes in the differential in the setting of upper extremity injury in a small child. Radiographs are negative and serve only to exclude the presence of bony injury when the diagnosis is not clear. (From Walters MM, Robertson RL, eds. *Pediatric Radiology: The Requisites*, 4th ed. Philadelphia: Elsevier; 2017: Fig. 7.102.)



Fig. 722.5 Radiograph of an adolescent with Madelung deformity.

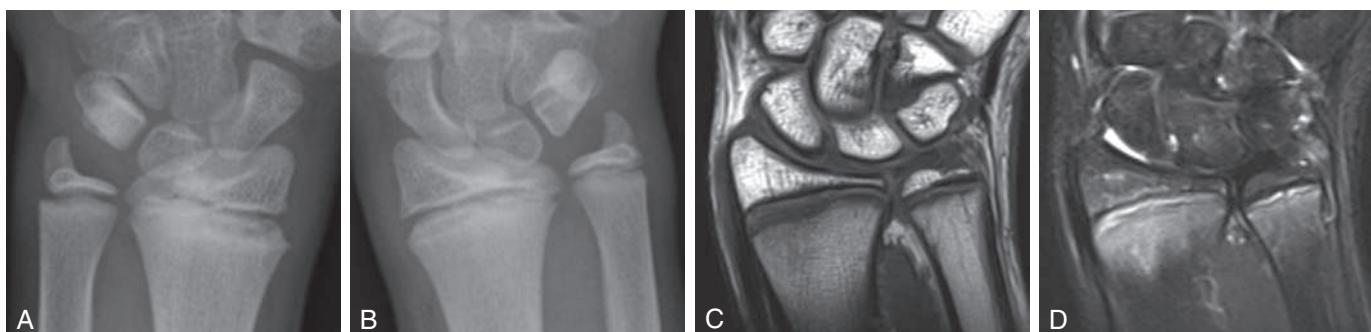


Fig. 722.6 Gymnast's wrist. A and B, Posteroanterior radiographs of the bilateral wrists show widening and irregularity of the distal radial physis. Abnormal linear lucency is seen in the metaphyses, with surrounding sclerosis noted. Findings reflect disrupted growth at the physes. C, Coronal T1 and D, coronal T2 magnetic resonance images with fat saturation show similar abnormality at the distal radial physis, along with abnormal increased fluid signal along the metaphysis. (From Walters MM, Robertson RL, eds. *Pediatric Radiology: The Requisites*, 4th ed. Philadelphia: Elsevier; 2017: Fig. 7.107.)

In cases where significant damage is seen in the distal radius physis, surgery may be indicated to prevent future morphologic changes in the wrist. Surgery may include epiphysiodesis of the radius and ulna, shortening of the ulna, and TFCC repair.

Ganglion

The wrist joint articulation is lubricated with synovial fluid, which is produced by the synovial lining of the joint and maintained within the joint by the joint capsule. A defect in the capsule can allow fluid to leak from the joint into the soft tissues, resulting in a ganglion. The term *cyst* is a misnomer, because this extraarticular collection of fluid does not have its own true lining. The defect in the capsule can occur as a traumatic event, although trauma is rarely a feature of the presenting history. The fluid usually exits the joint in the interval between the scaphoid and lunate, resulting in a ganglion located at the dorsoradial aspect of the wrist. Ganglia can occur at other locations, such as the volar aspect of the wrist, or in the palm because of leakage of fluid from the flexor tendon sheaths. Pain is not commonly associated with ganglia in children, and when it is, it is unclear whether the cyst is the cause of the pain. The diagnosis is usually evident on physical examination, especially if the lesion transilluminates. Extensor tenosynovitis and anomalous muscles can mimic ganglion cysts, but radiography or MRI is not routinely required. Ultrasonography is an effective, noninvasive tool to support the diagnosis and reassure the patient and family.

Treatment

Regarding the treatment of ganglia in children, consider the vowels AEIOU.

Aspiration: Simple aspiration of the fluid has a high recurrence rate and is painful for children given the large-bore needle required to aspirate the gelatinous fluid. However, in older children who would like to try and decompress the cyst before considering surgery, this may be reasonable.

Excision: Surgical excision, including excision of the stalk connecting the ganglion to its joint of origin, has a high success rate, although the ganglion can recur.

Injection: Aspiration of the cyst and a simultaneous injection of a corticosteroid have been shown to be effective in treating recurrence in children.

Observation: Up to 80% of ganglia in children <10 years of age resolve spontaneously within 1 year of being noticed. If the ganglion is painful or bothersome and the child is >10 years of age, treatment may be warranted.

Ultrasound: For children's parents who are concerned about the mass and want a radiographic study to confirm the diagnosis, ultrasound is a noninvasive test to confirm the diagnosis.

HAND

The hand and fingers allow for complex and fine manipulations. An intricate balance among extrinsic flexors, extensors, and intrinsic

Table 722.3 Classification of Camptodactyly

TYPE	CHARACTERISTICS
I	Congenital, no sex bias, small finger only
II	Acquired between 7-11 yr, typically progressive
III	Severe, significant contracture, bilateral and associated with other musculoskeletal syndromes

Adapted from Kozin SH. Pediatric hand surgery. In: Beredjiklian PK, Bozentka DJ, eds. *Review of Hand Surgery*. Philadelphia: WB Saunders; 2004:223-245.

**Fig. 722.7** Clinodactyly of the thumb.**Table 722.4** Syndromes Associated with Polydactyly*

Carpenter syndrome
Ellis-van Creveld syndrome
Meckel-Gruber syndrome
Polysyndactyly
Trisomy 13
Orofaciodigital syndrome
Rubinstein-Taybi syndrome
Bardet-Biedl syndrome
Meckel-Gruber syndrome
Pallister-Hall syndrome
Short Rib-polydactyly syndromes (type I, II)

*There are many syndromes with polydactyly; this is a partial list.

Table 722.5 Wassel Classification of Thumb Duplication

TYPE	CHARACTERISTICS
I	Bifid distal phalanx
II	Duplicate distal phalanx
III	Bifid proximal phalanx
IV	Duplicate proximal phalanx
V	Bifid metacarpal
VI	Duplicate metacarpal
VII	Triphalangeal component

Data from Wassel, HD. The results of surgery for polydactyly of the thumb: a review. *Clin Orthop.* 1969;125:175-193.

Type A is a well-formed digit. Type B is a small, often underdeveloped supernumerary digit.

Treatment

The initial treatment for clinodactyly is observation. For severe deformities and for those affecting the thumb, surgery may be indicated. Surgery is technically demanding. Bracket resections, corrective osteotomies, and growth plate ablations are the most common procedures performed to correct the observed angular deformities. Results are good, and recurrences are few.

Polydactyly

Polydactyly or duplication of a digit can occur either as a radial deformity (involving the thumb), central (index, middle, or ring), or as an ulnar deformity (involving the small finger) (Table 722.4). Each has an inherited and genetic component. Transmission is typically in an autosomal dominant pattern and has been linked to differences in genes localized to chromosome 2.

Duplication of the thumb has been subdivided into seven types by Flatt and Wassel based on the degree of duplication (Table 722.5). Small finger duplication has been further subdivided into two types.

Thump Hypoplasia

Hypoplasia of the thumb is a challenging condition for both the patient and the doctor. The thumb represents ~40% of hand function. A less-than-optimal thumb can severely limit a patient's function as they grow and develop. Hypoplasia of the thumb can range from being mild with slight shortening and underdeveloped musculature to complete

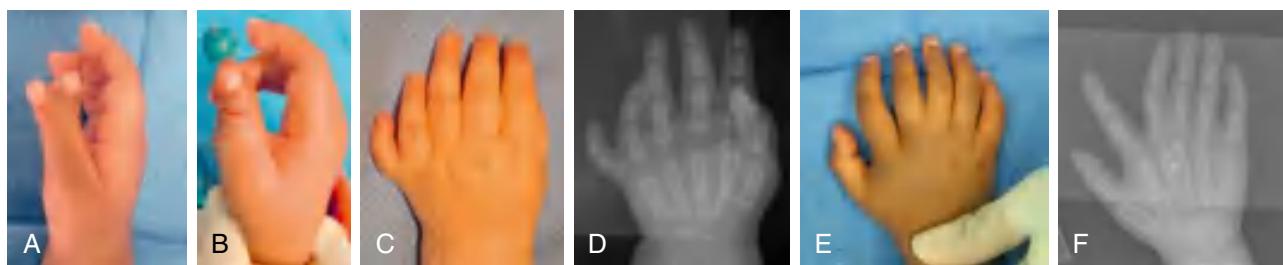


Fig. 722.8 A and B, Preoperative and postoperative pictures of a Wassel II thumb duplication. C, Clinical photograph. D, Radiograph postaxial polydactyly. E, Clinical photograph. F, Radiograph of central polydactyly.

absence of the thumb. Radiographs are useful to help determine osseous abnormalities. The most important finding on physical exam is the presence or absence of a stable carpometacarpal (CMC) joint. This finding helps guide surgical treatment.

Treatment

If the thumb has a stable CMC joint, reconstruction is advised. Key elements of thumb reconstruction include rebuilding the ulnar collateral ligament of the metacarpophalangeal joint, tendon transfers to aid thumb abduction, and procedures to deepen the web space.

If a stable CMC joint is not present or the thumb is completely absent (Fig. 722.9A), pollicization (surgical construction of a thumb from a finger) is the definitive treatment (see Fig. 722.9B). Pollicization is a complex procedure rotating the index finger along its neurovascular pedicle to form a thumb. This procedure is typically performed at around 1 year of age and may be followed by subsequent procedures to deepen the web space or augment abduction.

Syndactyly

Failure of the individual digits to separate during development produces syndactyly. Syndactyly is one of the more common anomalies observed in the upper limb (Table 722.6). It is seen in 0.5 of 1,000 live births. Syndactyly can be classified as simple (skin attachments only), complicated (bone and tendon attachments), complete (fusion to the tips, including the nail), or incomplete (simple webbing).

Treatment

Division of conjoined digits should be considered before the second year of life. Border digits should be divided earlier (3-6 months) because of concern for tethered growth of digits of unequal length. Digits of similar size, such as the index, middle, and ring, may wait until the child is older to consider separation. Reconstruction of the web space and nail folds as well as appropriate skin-grafting techniques must be used to ensure the best possible functional and cosmetic result (Fig. 722.10).

Fingertip Injuries

Young children commonly sustain crush injuries to the fingertips from doorjams, car doors, and other tight spaces. Injury can range from a simple subungual hematoma to complete amputation of part or the entire fingertip. Radiographs are important to rule out fractures. Physisal fractures associated with nailbed injuries are open fractures with a high risk of osteomyelitis, growth arrest, and deformity if not treated correctly.

The treatment of the soft tissue injury depends on the type of injury. For suture repairs, only absorbable sutures should be used. Removal of sutures from a young child's fingertip can be difficult and may require sedation or general anesthesia. If a subungual hematoma exists but the nail is normal and no displaced fracture is present, the nail need not be removed for nailbed repair. If the nail is torn or avulsed, the nail should be removed, and the nailbed and skin should be inspected and repaired with absorbable sutures where appropriate.

If the fingertip is completely amputated, treatment depends on the level of amputation and the age of the child. Distal amputations



Fig. 722.9 A, Congenital absence of the thumb. B, Postsurgical image after pollicization.

of skin and fat in children <2 years of age can be replaced as a composite graft with a reasonable chance of surviving. Similar amputations in older children can heal without replacing the skin if no bone is exposed and the amputated area is small. A variety of coverage procedures exist for amputations through the midportion of the nail. Amputations at or proximal to the proximal edge of the fingernail should be referred emergently to a replant center for consideration for microvascular replantation. When referring, all amputated parts should be saved, wrapped in saline-soaked gauze, placed in a watertight bag, and then placed in ice water. Ice should never directly contact the part because it can cause severe osmotic and thermal injury.

Trigger Thumb and Fingers

The flexor tendons for the thumb and fingers pass through fibrous tunnels made up of a series of pulleys on the volar surface of the digits.

These tunnels can become tight at the most proximal or first annular pulley. Swelling of the underlying tendon occurs, and the tendon no longer glides under the pulley. In children, the most common digit involved is the thumb. Trigger thumbs are not congenital deformities but rather are developmental and most frequently occur before 2 years

Table 722.6 | Syndromes Associated with Syndactyly*

Apert syndrome
Carpenter syndrome
Chotzen syndrome
de Lange syndrome
Fanconi pancytopenia
Fetal hydantoin syndrome
Holt-Oram syndrome
Laurence-Moon-Biedl syndrome
Noack syndrome
Orofaciodigital syndrome
Pfeiffer syndrome
Poland syndrome
Polysyndactyly
Trisomy 13
Trisomy 18
Trisomy 21

*There are many more syndromes associated with syndactyly; this list is not all-inclusive.

of age. The incidence of trigger thumb is approximately 3 per 1,000 children at 1 year of age. A history of trauma is rare, and the condition is often painless. Overall function is rarely impaired. A trigger thumb typically manifests with the inability to fully extend the thumb interphalangeal joint. A palpable nodule can be felt in the flexor pollicis longus tendon at the base of the thumb metacarpal phalangeal joint volarly. Other conditions can mimic trigger thumb, including the thumb-in-palm deformity of cerebral palsy. Similar findings in the fingers (index through small) are much less common and may be associated with inflammatory conditions such as juvenile idiopathic arthritis (Fig. 722.11).

Treatment

Trigger thumbs spontaneously resolve in up to 30% of children who are diagnosed before 1 year of age. Spontaneous resolution beyond that age is uncommon. Corticosteroid injections are effective in adults but are not effective in children and risk injury to the nearby digital nerves. Surgical release of the first annular pulley is curative and is generally performed between 1 and 3 years of age. Treatment of trigger fingers other than the thumb in children involves evaluation and treatment of any underlying inflammatory process and in some cases surgical decompression of the flexor sheath and possible flexor tendon partial excision.

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Fig. 722.10 Preoperative (A and B) and postoperative (C and D) pictures of a simple syndactyly.

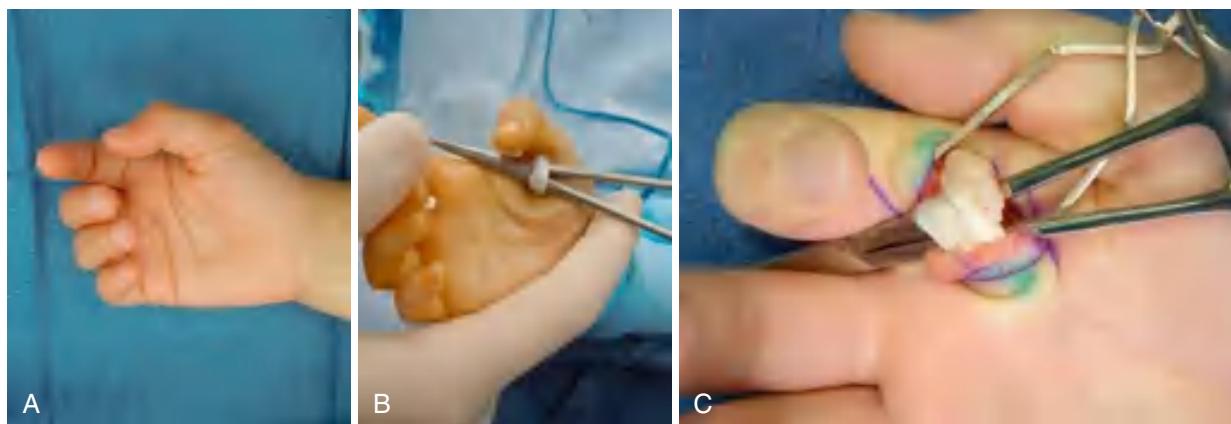


Fig. 722.11 A, Clinical picture of trigger thumb in a 2 yr old; note flexed posture of the interphalangeal joint. B, Intraoperative picture of flexor tendon following release of A1 pulley. C, Intraoperative picture of benign growth along flexor tendon causing triggering in an index finger.

Chapter 723

Arthrogryposis

Christine M. Goodbody, Helen M. Horstmann, and Richard S. Davidson

Arthrogryposis multiplex congenita refers to a heterogeneous group of muscular, neurologic, and connective tissue anomalies that present with two or more joint nonprogressive contractures at birth, as well as muscle weakness. It is associated with abnormal contraction of muscle fibers, causing reduced mobility with a decreased active and passive arc of motion. Arthrogryposis is not a specific diagnosis but a descriptive term with various etiologies and complex clinical features, including multiple congenital contractures of various limb joints. It is associated with over 300 different disorders encompassing malformation, malfunction, and neurologic deficiency (see Chapter 648.10).

Approximately 1% of all births show some form of contractures of the joints ranging from unilateral clubfoot to amyoplasia (the most severe), a condition characterized by pervasive, crippling contractures involving many joints. The overall incidence of arthrogryposis is 1/5,000–10,000 live births with equal gender ratios.

Although children with arthrogryposis may have many other problems, such as micrognathia and feeding issues, focus is on the orthopedic problems frequently seen in this group of children. In the absence of central nervous system lesions, many children have normal intelligence.

Etiology

The main cause of arthrogryposis is fetal akinesia or decreased fetal movement. The associated pattern of abnormalities is often referred to as the **fetal akinesia deformation sequence**. This sequence manifests as multiple joint contractures, oligohydramnios, craniofacial anomalies (e.g., micrognathia), and pulmonary hypoplasia because of lack of movement of the diaphragm and intercostal muscles. Intrinsic and extrinsic causes of fetal akinesia are categorized into six groups (Fig. 723.1) and include a multitude of disorders (Table 723.1).

Neurologic Abnormalities

Neurologic abnormalities are present in 70–80% of cases. Patchy damage to the anterior horn cells of the spinal cord can lead to characteristic limb posturing of arthrogryposis. Neurologic disorders, such as spinal muscular atrophy and anterior horn disease, are associated

with arthrogryposis; however, the type of anterior horn cell involvement is usually not from spinal muscular atrophy syndrome. Other less common neurologic disorders include neonatal myasthenia, myotonic dystrophy, olivo-ponto-cerebellar disorders, and neuronal migration anomalies.

Muscular Abnormalities

These rare abnormalities affect the function and structure of the muscles. **Amyoplasia**, the most common form of arthrogryposis, is associated with abnormally decreased fetal movement and is characterized by underdeveloped, contracted muscles causing joint deformity. The involved skeletal muscle is replaced by fatty or fibrous tissue. Some muscular diseases associated with arthrogryposis are muscular dystrophies, congenital myopathies (central core, nemaline, centronuclear), intrauterine myositis, and mitochondrial diseases.

Limited Intrauterine Spacing

Uterine constraint is rarely the primary cause of arthrogryposis. Maternal uterine anomalies will occasionally increase contractures of fetal limbs with arthrogryposis already existing. Other known causes are lack of amniotic fluid within the uterus, and tumors, such as fibroids, that can prevent movement by impinging on uterine space.

Connective Tissue Abnormalities

When the tendons, bones, joints, and joint lining develop atypically, the resulting decrease in fetal movement causes congenital contractures. Diseases such as **dystrophic dysplasia**, **campomelic dysplasia**, and **metatropic dysplasia** result from connective tissue not developing properly. These are specific diagnoses resulting in limited joint motion and not true distal arthrogryposis. In some cases, the connective tissue develops normally but does not attach to the proper location around a bone or joint, and the subsequent abnormal movement results in distal joint involvement.

Maternal Diseases

Maternal diseases, such as multiple sclerosis, diabetes mellitus, myasthenia gravis, maternal hyperthermia, infection (Zika virus), drugs, and trauma, are associated with an increased incidence of arthrogryposis. In approximately 10% of neonates born to mothers with myasthenia gravis, maternal antibodies enter the fetal circulation through the placenta, causing transient myasthenia gravis; this inhibits fetal acetylcholine receptors, which leads to damaged fetal muscles.

Intrauterine Vascular Compromise

Abnormal fetal blood supply may be associated with arthrogryposis. This occurs when inadequate vascular supply to the fetus causes fetal hypoxia resulting in anterior horn cell death, which, in turn, decreases neurologic and myologic function. The result is fetal akinesia and secondary joint contractures. Multiple congenital contractures have been reported in individuals after bleeding throughout pregnancy or after a failed attempt at terminating the pregnancy.

Classification

Arthrogryposis multiplex congenita is divided into subgroups with different signs, symptoms, and causes as a practical way to make a differential diagnosis. However, given the wide spectrum of disease presentation and etiology, no one classification system exists that is entirely comprehensive. Disorders involving primarily the limbs, such as amyoplasia and distal arthrogryposis, are the most common subgroups. Disorders involving limbs and other body parts typically represent a form of **multiple pterygium syndrome**, which is characterized by weblike membranes that form across joints, affecting a child's ability to extend those joints and causing fixed flexion deformities. Disorders with limb involvement and abnormal neurologic function are caused by atypical central nervous system development, peripheral nervous system abnormalities, damaged or absent anterior horn cells, or a combination thereof.

Amyoplasia, also known as *classic arthrogryposis*, is a sporadic symmetric disorder that causes fibrotic replacement of the muscles. Symptoms include internally rotated and adducted shoulders, extended

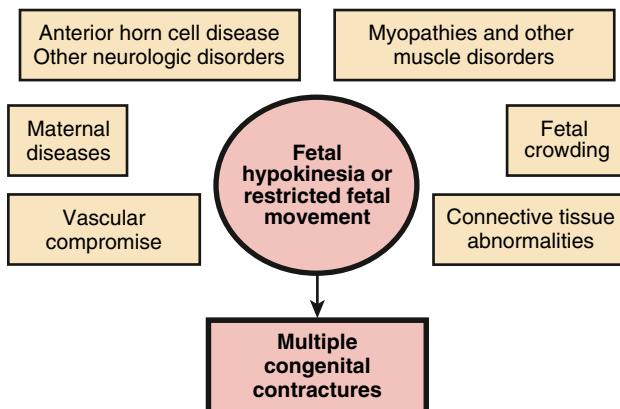


Fig. 723.1 Etiology of arthrogryposis. (Data from Hall JG. Arthrogryposis multiplex congenita: etiology, genetics, classification, diagnostic approach, and general aspects. *J Pediatr Orthop B*. 1996;6:159–166.)

Table 723.1 Associated Etiologies of Arthrogryposis

ARTHROGRYPOSIS CAUSED BY NERVOUS SYSTEM DISORDERS	
• Focal anterior horn cell deficiency	
• Generalized anterior horn cell deficiency	
• Structural brain disorder/damage	
• Uncertain location	
(Spastic conditions are excluded)	
DISTAL ARTHROGRYPOSIS SYNDROMES	
• Type I dominant distal	
• Type IIa dominant distal (Freeman-Sheldon syndrome)	
• Digitotalar dysmorphism	
• Trismus pseudocamptodactyly	
• Distal distribution, type not specified	
PTERYGIUM SYNDROMES	
• Multiple pterygium syndrome	
• Lethal multiple pterygium syndrome	
• Popliteal pterygium syndrome	
• Ptosis, scoliosis, pterygia	
• Antecubital webbing syndrome (Liebenberg)	
MYOPATHIES	
• Emery-Dreifuss muscular dystrophy	
• Hypotonia, myopathy, mild contractures	
ABNORMALITIES OF JOINTS AND CONTIGUOUS TISSUE	
• Congenital contractual arachnodactyly	
• Freeman-Sheldon syndrome	
• Laxity or hypertonicity with intrauterine dislocation and contractures	
• Larsen syndrome	
• Spondyloepimetaphyseal dysplasia with joint laxity	
• Trisomy 18, extended breech position with bilateral hip dislocation	
• Siblings with bifid humeri, hypertelorism, and hip and knee joint dislocations	
SKELETAL DISORDERS	
• Diastrophic dysplasia	
• Parastremmatic dysplasia	
• Kniest dysplasia	
• Metatropic dysplasia	
• Campomelic dysplasia	
• Schwartz syndrome	
• Fetal alcohol syndrome with synostoses	
• Osteogenesis imperfecta with bowing/contractures	
INTRAUTERINE/MATERNAL FACTORS	
• Fetal alcohol syndrome with contractures	
• Infections	
• Untreated maternal systemic lupus erythematosus	
• Intrauterine fetal constraint	
• Deformity (pressure)	
• Amniotic fluid leakage	
• Multiple pregnancies	
• Intrauterine tumors	
• Disruption (bands)	
MISCELLANEOUS	
• Pseudotrisomy 18 with contractures	
• Roberts pseudodthalidomide syndrome	
• Deafness with distal contractures	
• VACTERL association	
• Multiple abnormalities and contractures not otherwise specified	
• ARC	
SINGLE JOINT	
• Campomelia	
• Symphalangism	
• "Trigger" finger	

ARC, Arthrogryposis, renal tubular acidosis, cholestasis; VACTERL, vertebral defects, imperforate anus, congenital heart disease, tracheoesophageal fistula, renal and limb defects.

Modified from Mennen U, Van Heest A, Ezaki MB, et al. Arthrogryposis multiplex congenita. *J Hand Surg Br*. 2005;30(5):468–474. Copyright 2005 The British Society for Surgery of the Hand.

elbows, pronated forearms, flexed fingers and wrists, dislocated hips, feet with severe equinovarus contractures, and extended knees. Involved muscles are hypoplastic and fibrotic. Often, patients have midfacial hemangioma. Intelligence is usually normal (Figs. 723.2 and 723.3).

Distal arthrogryposis is an autosomal dominant disorder that primarily affects the distal joints of the limbs. Characteristics of the upper limbs are medially overlapping fingers, clenched fists, ulnar deviation of fingers, camptodactyly, and hypoplasia. Lower limbs show talipes equinovarus, calcaneovalgus, vertical talus, or metatarsus varus (Fig. 723.4), in addition to limited motion at the involved joints. Ten different types of distal arthrogryposis have been categorized based on specific traits they share with each other (Table 723.2).

MANAGEMENT OF ORTHOPEDIC PROBLEMS OF ARTHROGRYPOSIS

When a child is born with arthrogryposis, the many stiff or dislocated joints pose issues of timing and best practices of management. The overarching goal of management in the lower extremities are plantigrade feet and joints that function to optimize ambulatory potential, whereas in the upper extremity, the aim is largely the ability to grasp, feed, and toilet independently. A child may have stiff elbows, dislocated hips; dislocated, hyperextended, or contracted knees; and clubfeet (Fig. 723.5). The stiffness and deformity need to be aggressively addressed through a combination of modalities. A team of clinicians, including therapists for the upper and lower extremities, orthotists, and orthopedic surgeons, will be involved.

Initially, passive range-of-motion exercises and judicious splinting directed and assisted by physical and occupational therapy will help to address the various deformities. Splinting and casting can be augmented by a taping program that can be taught to the family so that the taping can be redone frequently to take advantage of improved range of motion. The ingenuity of the therapists and/or orthotists to create the right splints and braces using appropriate thermoplastics, neoprene, Velcro, and other materials can be effective (Fig. 723.6).

The therapeutic and orthopedic goal for the child with arthrogryotic limb deformities is to achieve maximal joint motion and to optimize joint position for function. In the lower extremities, the foot needs to be plantigrade. The knees need to have optimal motion for sitting and standing. Hips need to be stabilized, especially if the child has walking potential. In the upper extremities, in cases where there is extreme stiffness, the goals should include positioning of one arm for feeding and the other for toileting. Two-handed activities require some symmetry, which can be a challenging goal with extreme contractures and limited muscle strength. Serial casting may be beneficial in correcting joint contractures. Although scoliosis is common, it usually does not become a problem until adolescence (see Chapter 720).

FOOT PROBLEMS

Clubfoot deformities are the most commonly seen deformities with arthrogryposis (Fig. 723.7). A clubfoot has components of hindfoot equinus, midfoot varus, and forefoot adduction. Clubfeet in arthrogryposis tend to be more resistant to improvement than in idiopathic cases, but the traditional methods of treatment are nevertheless employed. Casting is begun shortly after birth in a method known as the Ponseti method. Casts are changed weekly until a plateau is reached, then heel cord lengthening is needed. Other deformities such as vertical talus are also seen and are addressed in a similar approach, although with case-appropriate differences in casting techniques (see Chapter 715).

Persistent stiffness often leads to more comprehensive soft tissue releases. This is typically done around age 6–12 months and is followed by 3 months of further casting and additional bracing as needed, especially as the foot is growing. When deformities are not corrected in early childhood, additional bony surgery may be needed later. Some of the approaches to this involve bony wedge osteotomies, lateral column lengthening, bone decancellation, or talectomy. Ring or multiaxial monolateral external fixation with or without osteotomies are used in late correction of residual deformities.



Fig. 723.2 Infant with stiff elbows, wrists, fingers, dislocated left hip, valgus stiff knees, and clubfeet.



Fig. 723.4 Infant with club feet, stiff knees, dislocated hips, stiff fingers, and facial hemangioma.



Fig. 723.3 Infant with stiff elbows, wrists, fingers, dislocated left hip, clubfeet, and micrognathia.

Children with significant deformities are often in ankle foot orthoses through much of their lives to avoid deformity recurrence and to augment the standing base caused by weak leg muscles. A plantigrade, pain-free, stable foot is the goal of foot management. Foot stiffness is anticipated and unavoidable in arthrogryposis involving the foot.

KNEE PROBLEMS

Knee issues in patients with arthrogryposis may include knee extension or flexion contracture, subluxation, and stiffness. Knee flexion contracture is more common in arthrogryposis and is often resistant to nonsurgical treatment. It can be structurally complex and associated with skin webbing known as pterygiums, which require Z-plasty lengthenings. In the case of a flexion contracture, the quadriceps musculature is often deficient and weak. When a trial of casting and splinting of the knee contractures is insufficient, surgical intervention with hamstring lengthenings and posterior knee capsular releases are often needed. Soft tissue relaxation by femoral shortening has also shown benefit.

In the case of knee hyperextension, the quadriceps are sometimes fibrotic and weak despite seeming to overpower the hamstrings. Casting and splinting should begin shortly after birth, which can be done in conjunction with clubfoot casting as needed following the principles of Ponseti. If splinting and therapy fail, lengthening of the quadriceps can be achieved through a number of surgical techniques that may include detachment of the rectus femoris and lengthening of the quadriceps either percutaneously or through a mini open procedure, which may minimize scarring.

Long-standing stiffness may lead to joint surface flattening and other bony abnormalities that can permanently reduce the arc of motion. Repositioning the arc of motion through bony osteotomies may improve sitting or standing. Follow-up bracing can help to compensate for weak, fibrotic muscles of the legs. Use of guided growth plates and screws may also be of benefit.

HIP PROBLEMS

Teratologic hip dislocations are common within the spectrum of arthrogryposis and usually require open reduction of the hip. Hips in a child with less upper-extremity involvement and more supple hips that are not pathologically stiff may respond to early treatment with a Pavlik harness. Coexisting knee hyperextension should

Table 723.2 A Classification System and Clinical Features of Distal Arthrogryposes

TYPE	DESCRIPTION
I	Characteristic clinical features are camptodactyly and talipes equinovarus with possible concomitant shoulder and hip contractures. The DA1 variant is determined by a gene located on chromosome 9.
II	The phenotype was first described in 1938 as the Freeman-Sheldon syndrome, where contractures of fingers and toes are accompanied by kyphosis, scoliosis, and malformations of the facial skeleton with characteristic facial appearance: narrow mouth, wide cheeks, an H-shaped chin dimple, small wide-based nose, high palate, and small tongue. Growth retardation, inguinal hernia, and cryptorchidism have also been reported. Another name of this syndrome is "whistling face" syndrome. The Freeman-Sheldon syndrome is currently classified as DA2A, as a separate DA2B subtype, known as Sheldon-Hall syndrome has been described; this syndrome combines clinical features of DA1 (hand and foot contractures) and some features of DA2 (prominent nasolabial folds, slanted down-facing eyes, and narrow mouth) and is currently considered to be probably the most common type of distal arthrogryposis.
III	Also known as Gordon syndrome, this rare syndrome is characterized by low stature and palatoschisis.
IV	Rare. Contractures with severe scoliosis.
V	Contractures with ocular signs and symptoms such as limited eye motion, ptosis, strabismus, and the absence of typical hand flexion creases. Chest wall muscle abnormalities have also been observed, potentially causing restricted respiratory movements and, consequently, pulmonary hypertension.
VI	Similar to DA3, DA4; very rare, characterized by sensorineural auditory abnormalities.
VII	Difficulties in mouth opening (trismus) and pseudocamptodactyly: wrists position in palmar flexion with MCP joints in extension. Sometimes accompanied by low stature and knee flexion contractures.
VIII	Autosomal dominant multiple pterygium syndrome.
IX	Beals syndrome, i.e., congenital arachnodactyly with contractures of small joints of the fingers. Patients with this type of arthrogryposis are tall and slender, phenotypically resembling Marfan syndrome but without cardiovascular abnormalities.
X	Congenital plantar flexion contractures of the foot.

From Kowalczyk B, Feluś J. Arthrogryposis: an update on clinical aspects, etiology, and treatment strategies. *Arch Med Sci*. 2016;12(1):10–24. [Table 1](#).

first be treated with physical therapy and serial casting to allow for appropriate Pavlik harness fitting. However, careful observation of the hip during knee flexion is necessary because tightening of the quadriceps and hip flexors can push the hip into posterior dislocation. Once some knee flexion has been achieved, the Pavlik harness can be useful in further flexing the knee and maintaining hip stability in the infant. Most often, the hips are stiff and not reducible by closed means. For these, open reduction with pelvic reconstruction

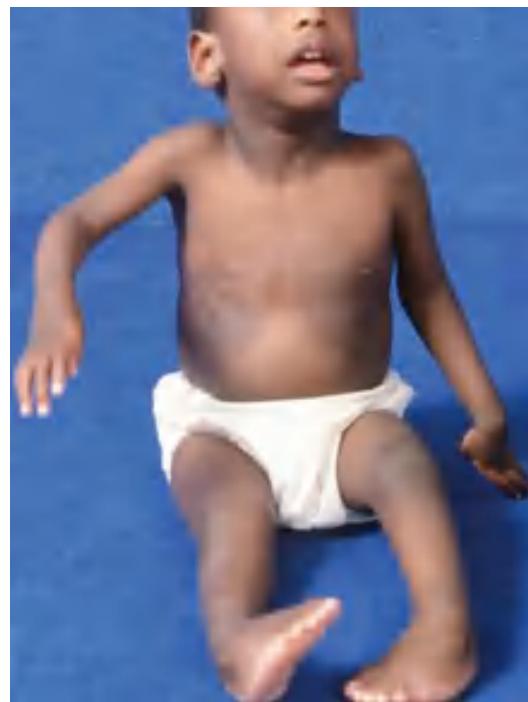


Fig. 723.5 Child with stiff elbows, wrists, knees, and clubfeet.



Fig. 723.6 Infant with splints to extend metatarsophalangeal joints, wrists, and knees.

and femoral osteotomy are commonly required, typically at 1 year of age. There is some controversy about reducing bilateral hip dislocations because a high failure rate can result in asymmetry of the pelvis, pain, leg length inequality, and stiffness. If a child has little



Fig. 723.7 Clubfeet in infant with arthrogryposis.

ambulatory potential, they may do as well retaining the bilateral hip dislocations and positioning the hips for sitting. Management decisions should be made in conjunction with the family and guided by a pediatric hip surgeon.

Ambulation

As would be expected, walking is more difficult for children with arthrogryposis because of the muscle weakness and limited joint motion. Children with arthrogryposis who walk have lower activity levels and take fewer steps than their peers. Not surprisingly, muscle fatigue and pain on exertion are common.

UPPER EXTREMITY PROBLEMS

If splinting and a movement exercise program do not result in optimally functional upper extremities, surgical management may improve use of the arms of the child with arthrogryposis. A typical child with arthrogrypotic involvement of the upper extremities has internally rotated arms, extended elbows, flexed wrists, and thumb-in-palm or clasp-thumb deformities (see Figs. 723.2 and 723.3).

Treatment is geared toward optimizing use of the arms and hands, particularly for critical activities of daily living, such as feeding and toileting. Therapy to improve motion of the joints is started immediately after birth. Pediatric hand therapists are the optimal leaders of the mobility treatment program. Therapy is augmented by use of splints so that less-extensive surgery will ultimately be required. The elbow is the critical length adjuster of the arm, allowing the arm to reach out as is necessary for toileting or to approach the mouth for feeding. If necessary, lack of these motions can be compensated for with modified silverware and other adaptive equipment, including arm extenders for grabbing.

Surgery of the Upper Extremity

Surgical correction of arthrogrypotic upper extremity contractures should be started after 1-3 months and completed by age 12 months so that the child can optimize his or her motor development. This allows for improved results by optimizing the joint growth remodeling plasticity. One-stage procedures yield the best results. Delays in surgery result in more problems of intraarticular adhesions as well as fixed joint incongruity.

Shoulder

Because of the rotational capacity of the shoulder, derotation osteotomy of the humerus is only occasionally needed. This is usually done in later childhood.

Elbow

A stiff elbow that does not respond to therapy requires surgical intervention starting with soft tissue and capsular release. Capsulotomy of the posterior elbow combined with a V-Y or Z reconstructive lengthening of the triceps allows improved elbow flexion. Muscle transfer to the forearm can permit active elbow flexion; however, each child needs individual assessment as to an available flexor source. The triceps is commonly used, but caution must be exerted into the overall muscle balance because use of the triceps can create elbow flexion overpowering and an opposite contracture.

Wrist

Wrist flexion deformity is improved with soft tissue balancing as well as partial carpectomies. The carpectomies need to be trapezoidal with more removed from the dorsum and the radial side to balance the wrist flexion contracture as well as the tendency for ulnar deviation. Thumb adduction may require an adductor release with an opponensplasty. Tendon transfers such as transfer of the extensor indicis pollicis to the extensor pollicis longus is helpful for improved function of the thumb in clasp thumb deformity.

Finger stiffness and wrist contractures often respond to therapy and bracing without need for surgery.

Scoliosis

Scoliosis develops in some children with arthrogryposis, with the reported incidence ranging from 2.5–66%. Scoliosis can be congenital or paralytic. It is often accompanied by hip contractures associated with hip dislocation and compensatory lumbar lordosis. Curves <30 degrees can be treated initially with bracing in a thoracolumbar spinal orthosis (TLSO brace). After 40 degrees, spinal fusion is generally warranted.

Surgical Staging

Surgical treatment of the lower limbs usually begins distally and works proximally. The feet are corrected around 6 months of age, the knees around 8 months of age, and the hips around 12 months of age because pelvic osteotomy is often needed to stabilize the hips properly.

The upper extremities are corrected during infancy when the child is seen early. Hand, physical, and occupational therapy are a critical part of the team to optimize function before and after surgery. Further surgery during childhood may be needed to optimize functional use of the upper and lower extremities.

Prognosis

Although most patients with arthrogryposis are ambulatory into adulthood, fewer are entirely independent, and many have pain or limitations in walking and standing. Surgical advancements in upper extremity positioning have improved function, and procedures to correct lower extremity contractures, including not only surgery but also casting for clubfeet, have increased long-term ambulatory potential. However, there is significant variability in this population, and further work must be done to optimize intervention techniques and their appropriate utilization.

Chapter 724

Common Fractures

Jason B. Anari, Alexandre Arkader, and Lawrence Wells

Trauma is a leading cause of death and disability in children older than 1 year of age (see [Chapter 14](#)). Several factors make fractures of the immature skeleton different from those involving the mature skeleton. The anatomy, biomechanics, and physiology of the pediatric skeletal system differ from those of adults, resulting in different fracture patterns ([Fig. 724.1](#)), diagnostic challenges, and management techniques. Children have a high functional demand and expectations while carrying concerns regarding remaining skeletal growth and development.

Epiphyseal lines, rarefaction, dense growth lines, congenital fractures, and pseudofractures may appear on radiographs, which make it challenging to identify and differentiate an acute fracture. Although most fractures in children heal well, some fractures have poor outcomes if handled with insufficient expertise. The differences in the pediatric skeletal system predispose children to injuries different from those of adults. Important differences are the presence of periosseous cartilage, **physes**, and a thicker, stronger, more osteogenic periosteum that produces new bone, called **callus**, more rapidly and in greater amounts. The pediatric bone is less dense and more porous than adult bone. The low density is from lower mineral content, and the increased porosity is the result of an increased number of haversian canals and vascular channels. These differences result in a comparatively lower modulus of elasticity and lower bending strength. The bone in children can fail either in tension or in compression; because the fracture lines do not propagate as in adults, there is less chance of comminuted fractures. Hence, pediatric bone can crush, splinter, and break incompletely (e.g., buckle fracture, greenstick fracture), as opposed to adult bone which generally breaks like glass and may comminute.

A common teaching is that joint injuries, dislocation, and ligament disruptions are infrequent in children. Damage to the physis is more likely. Although this is generally true, MRI studies show that ligament damage in ankle injuries may be more common than once thought. Interdigitating mammillary bodies and the perichondrial ring enhance the strength of the physes. Biomechanically, the physes are not as strong as the ligaments or metaphyseal bone. The physis is most resistant to traction and least resistant to torsional forces. The periosteum is loosely attached to the shaft of bone and adheres densely to the phyeal periphery. The periosteum is essentially injured in all fractures, but it is less likely to have complete circumferential rupture because of its

loose attachment to the shaft. This intact hinge or sleeve of periosteum lessens the extent of fracture displacement and assists in reduction and maintenance of fracture reduction. The thick periosteum, however, may act as an impediment to reduction, particularly if the fracture has penetrated the periosteum, or in reduction of a displaced growth plate fracture.

724.1 Unique Characteristics of Pediatric Fractures

Jason B. Anari, Alexandre Arkader, and Lawrence Wells

FRACTURE REMODELING

Remodeling is the third and final phase in the biology of fracture healing; it is preceded by the inflammatory and reparative phases. This occurs from a combination of appositional bone deposition on the concavity of deformity, resorption on the convexity, and asymmetric physeal growth. Thus reduction accuracy is somewhat less important than it is in adults (exceptions include intraarticular fractures) ([Fig. 724.2](#)). The three major factors that have a bearing on the potential for angular correction are skeletal age, distance from the physis, and orientation to the joint axis. Rotational deformity and angular deformity not in the axis of the joint motion have less potential for remodeling. Remodeling is greatest when the child has many years of growth remaining and when the fracture occurs close to the physis, has less deformity to remodel, and is adjacent to a rapidly growing physis (e.g., the proximal humerus or distal radius). Remodeling typically occurs over several months after the fracture until skeletal maturity. Generally, skeletal maturity is reached in postmenarchal females between 13 and 15 years of age and in males between 15 and 17 years of age.

OVERGROWTH

Physeal stimulation from the hyperemia associated with fracture healing may also cause overgrowth. It is usually more prominent in lower extremity long bones such as the femur. The growth acceleration is usually present for 6 months to 1 year after the injury. Femoral fractures in children younger than 10 years of age may overgrow up to 1-3 cm. If external fixation or casting is employed, bayonet apposition of bone may be preferred for younger children to compensate for the expected overgrowth. This overgrowth phenomenon will result in equal or near equal limb lengths at the conclusion of fracture remodeling if the fracture shortens less than 2 cm. After 10 years of age, overgrowth does not tend to occur, and anatomic alignment is recommended. In physeal injuries, growth stimulation is associated with use of implants or fixation hardware that can cause stimulus for longitudinal growth.

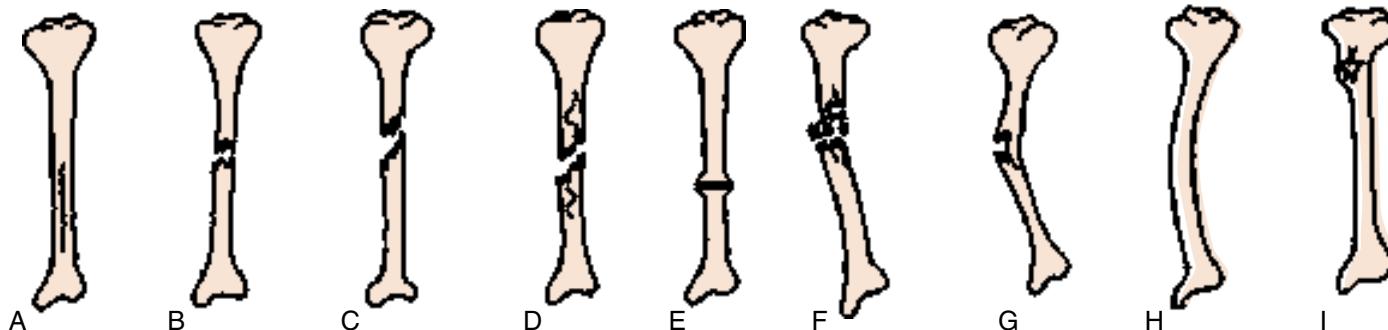


Fig. 724.1 Illustration of fracture patterns. A, Longitudinal fracture line parallel to bony axis. B, Transverse fracture line perpendicular to bony axis. C, Oblique fracture line at angle to bony axis. D, Spiral fracture line runs a curvilinear course to the bony axis. E, Impacted fractured bone ends compressed together. F, Comminuted fragmentation of bone into three or more parts. G, Greenstick bending of bone with incomplete fracture of convex side. H, Bowing bone plastic deformation. I, Torus buckling fracture. (From White N, Sty R. Radiological evaluation and classification of pediatric fractures. *Clin Pediatr Emerg Med*. 2002;3:94–105.)

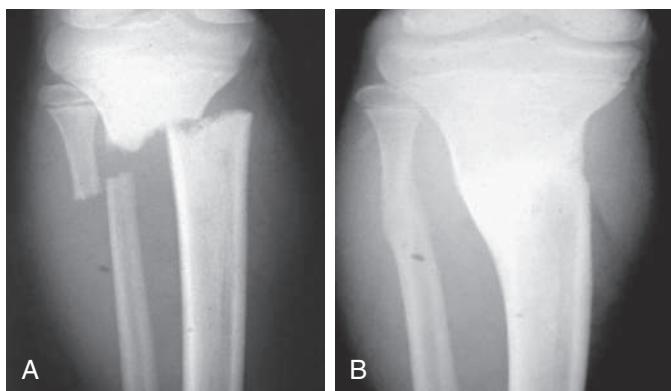


Fig. 724.2 Remodeling in children is often extensive, as in this proximal tibial fracture (A) and as seen 1 yr later (B). (From Dormans JP. *Pediatric Orthopedics: Introduction to Trauma*. Philadelphia: Mosby; 2005:38.)

PROGRESSIVE DEFORMITY

Injuries to the physes can be complicated by permanent or temporary growth arrest, leading to progressive limb deformity. The most common cause is complete or partial closure of the growth plate. This can occur in any long bone but is particularly seen in fractures involving the distal ulna, distal femur, and proximal tibia growth plates. An MRI is helpful for early diagnosis of growth arrest, as well as measurement of the percent of physisal closure after such an injury. Harris growth arrest lines may be observed in the setting of asymmetric growth and will point toward the area of growth arrest (Fig. 724.3). If these lines are parallel to the physis, this finding indicates that the growth plate is healthy. As a consequence of growth arrest, angular deformity or shortening, or both, can occur. The partial arrest may be peripheral, central, or combined. The magnitude of deformity depends on the specific physis involved, the degree of involvement, and the amount of growth remaining.

RAPID HEALING

Children's fractures heal more quickly than adults as a result of children's growth potential and thicker, more active periosteum. When children approach adolescence and maturity, the rate of healing slows and mirrors that of an adult.

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724.2 Pediatric Fracture Patterns

Jason B. Anari, Alexandre Arkader, and Lawrence Wells

The different pediatric fracture patterns are the reflection of a child's characteristic skeletal system. The majority of pediatric fractures can be managed by closed methods and heal well.

PLASTIC DEFORMATION

Plastic deformation is unique to children. It is most commonly seen in the forearm and occasionally the fibula. The fracture results from a force that produces microscopic failure on the tensile side of bone and does not propagate to the concave side (Fig. 724.4). The concave side of bone also shows evidence of microscopic failure in compression. The bone is angulated beyond its elastic limit, but the energy is insufficient to produce a fracture. Thus no fracture line is visible radiographically (Fig. 724.5). Although the plastic deformation is permanent, it is important to remember that children have great remodeling capability; for example, a 20-degree bend in the ulna of a 4-year-old child is expected to correct completely with growth. These findings inform "acceptability" of fracture alignment.



Fig. 724.3 A, Harris growth arrest lines on either side of the femur pointing centrally in the femur indicating a central growth arrest. B, Corresponding MRI image showing central growth arrest. (A, Courtesy Dr. Keith D. Baldwin, Children's Hospital of Philadelphia.)

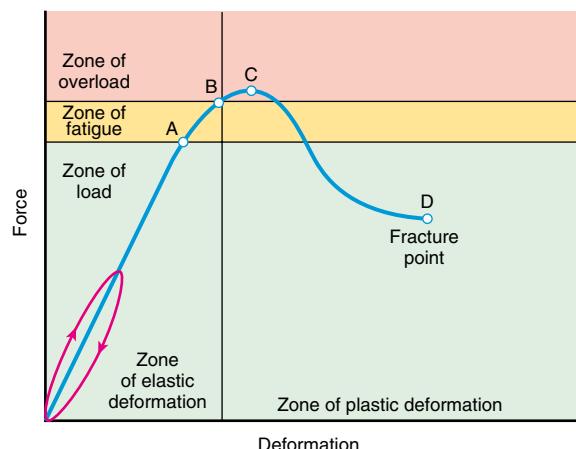


Fig. 724.4 Graphic relation of bony deformation (bowing) and force (longitudinal compression) showing that the limit of an elastic response is not a fracture but plastic deformation. If the force continues, a fracture results. A, Reversible bowing with stress; B, microfractures occur; C, point of maximal strength; between C and D, bowing fractures; and D, linear fracture occurs. (Modified from Borden S IV. Roentgen recognition of acute plastic bowing of the forearm in children. Am J Roentgen Radium Ther Nucl Med. 1975;125:524–530.)

BUCKLE OR TORUS FRACTURE

Buckle, or torus, fractures represent a failure in compression of the bone, usually occurring at the junction of the metaphysis and diaphysis. The distal radius is the most common location, but it may occur in other areas as well (Fig. 724.6). They are inherently stable, usually associated with an acceptable amount of angulation, and heal in 3–4 weeks with simple immobilization.

GREENSTICK FRACTURE

These fractures occur when the bone is bent and there is failure on the tensile (convex) side of the bone. The fracture line does not propagate to the concave side of the bone (Fig. 724.7). The concave side shows evidence of microscopic failure with plastic deformation. If the angulation at the fracture site is unacceptable, it is usually necessary to break the bone on the concave side because the plastic deformation recoils it back to the deformed position. It is important to distinguish this unicortical fracture pattern from buckle fractures, as these fractures are at greater risk of loss of reduction and often require a longer period of immobilization.

COMPLETE FRACTURES

Fractures that propagate completely through the bone are called complete fractures. These fractures may be classified as spiral, transverse, or oblique, depending on the direction and shape of the fracture lines. A rotational force is responsible for spiral fractures. Most spiral fractures



Fig. 724.5 Plastic deformation is a microfailure in tension without a visible fracture line. (Courtesy Dr. John Flynn, Children's Hospital, Philadelphia.)



Fig. 724.7 Greenstick fractures of the radial and ulnar diaphyses in an 8-yr-old boy. The fracture lines only extend through part of the cortex. (From Pai DR, Strouse PJ. Skeletal trauma. In: Coley BD ed. Caffey's Pediatric Diagnostic Imaging, 13th ed. Philadelphia: Elsevier; 2019: Fig. 142.5, p. 1435.)

Table 724.1 Salter-Harris Classification

SALTER-HARRIS TYPE	CHARACTERISTICS
I	Separation through the physis, usually through the zones of hypertrophic and degenerating cartilage cell columns
II	Fracture through a portion of the physis but extending through the metaphyses
III	Fracture through a portion of the physis extending through the epiphysis and into the joint
IV	Fracture across the metaphysis, physis, and epiphysis
V	Crush injury to the physis

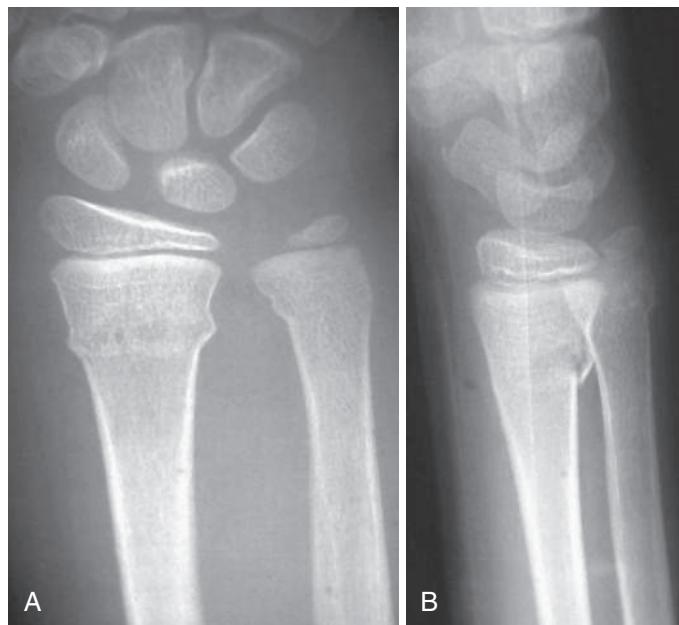


Fig. 724.6 Buckle fracture is a partial failure in compression. Anteroposterior (A) and lateral (B) radiographs of the distal radius. (From Dormans JP. Pediatric Orthopedics: Introduction to Trauma. Philadelphia: Mosby; 2005:37.)

are stable and heal quickly due to the large surface area; however, spiral fractures occurring as a result of a high-energy trauma may present with shortening of the bone and loss of alignment. Oblique fractures are defined by a 30-degree angle to the axis of the bone and are often unstable. The transverse fracture pattern occurs following a three-point

bending force and is amenable to successful reduction by using the intact periosteum from the concave side as a hinge.

EPIPHYSEAL FRACTURES

Fractures involving the epiphysis often involve the growth plate (physis); therefore the potential for growth disturbance leading to deformity or discrepancy exists, and long-term observation is necessary. The distal radial physis is the most injured physis. Salter and Harris (SH) classified physeal injuries into five groups (Table 724.1 and Fig. 724.8). This classification helps to predict the outcome of the injury and offers guidelines in formulating treatment. Most SH type I and II fractures usually can be managed by closed reduction techniques and do not require perfect alignment because they tend to remodel with growth, as long as there is enough growth remaining. One classic exception is the distal femur, where SH type II fractures are unstable and require anatomic reduction with adequate fixation. The SH type III and IV epiphyseal fractures involve the articular surface and require anatomic alignment (<2 mm displacement) to prevent any step off and realign the growth cells of the physis. SH type V fractures are usually not diagnosed initially. They manifest in the future with growth disturbance. Other injuries to the epiphysis are avulsion injuries of the tibial spine and muscle attachments to the pelvis. Osteochondral fractures are also defined as physeal injuries that do not involve the growth plate.

CHILD ABUSE

See also Chapter 17.

Fractures are the second most common manifestation of child abuse after skin injury (bruises, burns/abrasions). The orthopedic surgeon sees 30–50% of all nonaccidental traumas. Child abuse should be suspected in nonambulatory children with lower-extremity long-bone fractures. No fracture pattern or types are pathognomonic for

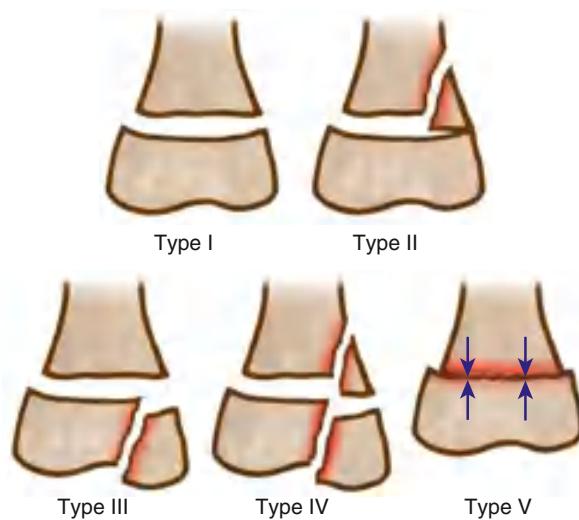


Fig. 724.8 Salter-Harris classification of physeal fractures, types I–V.

child abuse; any type of fracture can result from nonaccidental trauma (Table 724.2). **Transverse fractures** in long bones are the most prevalent, and **corner fractures** in the metaphysis are the most classic. The fractures that suggest nonaccidental injury include femur fractures in nonambulatory children (younger than age 18 months), distal femoral metaphyseal corner fractures, posterior rib fractures, scapular spinous process fractures, and proximal humeral fractures. Fractures that were unwitnessed or carry a suspicious or changing story or delayed presentation also warrant investigation. A full skeletal survey is essential in every suspected case of child abuse because it can demonstrate other fractures in different stages of healing. Radiographically, some systemic diseases mimic signs of child abuse, such as osteogenesis imperfecta, osteomyelitis, Caffey disease, vitamin C deficiency, and fatigue fractures. Many hospitals have a multidisciplinary team to evaluate and treat patients who are victims of child abuse; these teams are critical to engage early and preferably in the emergency room setting, as difficulty arises managing these emotionally charged issues in a clinic setting. Dedicated teams are most well equipped to identify and manage these issues. It is mandatory to report these cases to social welfare agencies.

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724.3 Upper Extremity Fractures

Jason B. Anari, Alexandre Arkader, and Lawrence Wells

PHALANGEAL FRACTURES

Finger fractures are among the most common fracture types in children. The different phalangeal fracture patterns in children include physeal, diaphyseal, and tuft fractures. The mechanism of injury varies from a direct blow to the finger to a finger trapped in a door (see Chapter 722). Crush injuries of the distal phalanx manifest with severe comminution of the underlying bone (tuft fracture), disruption of the nail bed, and significant soft tissue injury. These injuries are best managed with irrigation, tetanus prophylaxis, and antibiotic prophylaxis; antibiotics effective against staphylococci (e.g., first-generation cephalosporins) are usually appropriate, although the mechanism of injury may warrant other antibiotic coverage. Radiographs in patients with fingertip crush injuries should be scrutinized for evidence of a **Seymour fracture**, an open physeal fracture of the distal phalanx with possible interposition of the nail matrix. These patients are at higher risk of nail plate deformity and infection without surgical treatment. A **mallet finger** deformity is the inability to extend the distal portion

Table 724.2 Skeletal Injuries from Child Abuse

HIGH-SPECIFICITY FINDINGS

- Classic metaphyseal lesions
- Posterior rib fracture
- Scapular fracture
- Sternal fracture
- Spinous process fracture
- First rib fracture

MODERATE-SPECIFICITY FINDINGS

- Multiple fractures
- Fractures of differing age
- Spine fracture
- Complex skull fracture
- Physeal fractures of the long bones
- Digital fractures

LOW-SPECIFICITY FINDINGS

- Diaphyseal fractures of the long bones
- Simple skull fractures
- Clavicle fracture
- Subperiosteal new bone formation

From Coley BD, ed. *Caffey's Pediatric Diagnostic Imaging*, 13th ed. Philadelphia: Elsevier; 2019: Box 143.2, p. 1455; modified from Kleinman PK. *Diagnostic Imaging of Child Abuse*, 2nd ed. St. Louis, MO: Mosby; 1998.

of the digit and is caused by a hyperflexion injury. It represents an avulsion fracture of the physis of the distal phalanx. The treatment is continuous splinting of the digit in extension for 6 weeks. The physeal injuries of the proximal and middle phalanx are similarly treated with cast immobilization. The most common physeal finger fracture results from an abduction injury to the small finger. These fractures often require a closed reduction before immobilization. Diaphyseal fractures may be oblique, spiral, or transverse in fracture geometry. They are assessed for angular and rotational deformity with the finger in flexion. The patient should be asked to make a fist. All fingers should point toward the scaphoid. If they do not, malrotation is suspected, even in the presence of x-rays in which the bones appear minimally displaced. Malrotation or angular deformity may require correction to avoid finger crossover and to optimize hand function. These deformities are corrected with closed reduction, and, if unstable, they need surgical fixation with a percutaneous pin.

HAND FRACTURES

Metacarpal fractures are commonly seen in children or adolescents who strike a person or object with a closed fist. When metacarpal fractures are not displaced, they can be managed with splinting and/or casting. Displaced fractures are typically managed with closed reduction and casting. If reduction cannot be maintained, surgical stabilization may be required.

Fractures of carpal bones are rare in young children but become more common in adolescence. Most carpal bones are stable and can be treated with immobilization in a splint or cast. The scaphoid is the most commonly fractured carpal bone and presents with tenderness at the anatomic snuffbox. **Scaphoid fractures** may be difficult to visualize on initial radiographs; if clinical suspicion for fracture is high, the patient with negative initial radiographs should be placed in a thumb spica splint with a plan to repeat imaging in 14–21 days.

FOREARM FRACTURES

Fractures of the wrist and forearm are very common in children, accounting for nearly half of all fractures seen in the skeletally immature. The most common mechanism of injury is a fall on the outstretched hand. Of forearm fractures, 80% involve the distal radius and ulna, 15% involve the middle third, and the rest are rare fractures of the proximal third of the radius or ulnar shaft (Fig. 724.9). Most forearm fractures in younger children are torus or greenstick fractures. The torus fracture is an impacted fracture, and there is minimal soft tissue swelling or hemorrhage. They may be managed in either a short



Fig. 724.9 Common pediatric fracture patterns. A, Posteroanterior and (B) lateral radiographs of the wrist demonstrate a buckle fracture of the distal radial metaphysis (arrows). C, Radiograph of the forearm demonstrates a greenstick fracture of the radial shaft, with the fracture extending through a single cortex. D, Anteroposterior radiograph of the forearm shows an oblique fracture through the distal radial shaft, with plastic bowing deformity of the adjacent distal ulna. (From Walters MM, Robertson RL, eds. *Pediatric Radiology: The Requisites*, 4th ed. Philadelphia: Elsevier; 2017: Fig. 7.90.)

arm (below the elbow) cast or removable wrist splint and usually heal within 3–4 weeks.

Diaphyseal fractures can be more difficult to treat because the limits of acceptable reduction are much more stringent than for distal radial fractures. A significant malunion of a forearm diaphyseal fracture can lead to a permanent loss of pronation and supination, leading to functional difficulties. This is particularly true with malrotation of the fragments. Diaphyseal fractures are vulnerable to rotational malalignment because of insertion of the pronator muscle groups and the supinator groups. This malalignment is particularly hard to assess because the deformity is in the axial plane and is evaluated with anteroposterior (AP) and lateral radiographs (Fig. 724.10). The physical examination focuses on soft tissue injuries and ruling out any neurovascular involvement. The AP and lateral radiographs of the forearm and wrist confirm the diagnosis. Displaced and angulated fractures require manipulative closed reduction under general anesthesia or conscious sedation. They are immobilized in an above-elbow cast for at least 6 weeks. Bone fractures in older children and adolescents (>10 years of age) must be followed carefully as they often lose reduction. Loss of reduction and unstable fractures require open reduction and internal fixation. Fixation may be with intramedullary nails or plate fixation, which yield similar results.

DISTAL HUMERAL FRACTURES

Fractures around the elbow receive more attention because more aggressive management is needed to achieve an excellent result. Many injuries are intraarticular, involve the physeal cartilage, and can result in malunion or nonunion. Because the distal humerus develops from a series of ossification centers, these ossification centers can be mistaken for fractures by inexperienced eyes. Careful radiographic evaluation is an essential part of diagnosing and managing distal humeral injuries. It is important to remember that the distal humerus is only responsible for 20% of the growth of the humerus; therefore there is very low potential for remodeling. Observation of soft tissue swelling and tenderness is critical to pick up subtle injuries. Common fractures include separation of the distal humeral epiphysis (transphyseal



Fig. 724.10 A rotationally malaligned forearm fracture that initially had good alignment but lost reduction in the cast. Note that the radial styloid is visible, but the biceps tuberosity is not. The two should normally be 180 degrees from one another. These landmarks are sometimes hard to appreciate in children but were visible on other views in this child.

fracture), supracondylar fractures of the distal humerus, and epiphyseal fractures of the lateral condyle or medial epicondyle. The mechanism of injury is most frequently a fall on an outstretched arm. The physical examination includes noting the location and extent of soft tissue swelling, ruling out any neurovascular injury, specifically anterior interosseous nerve involvement or evidence of compartment syndrome. A transphyseal fracture in a very young child who does not have the reflex to keep the arm outstretched to break a fall should raise suspicion of child abuse. AP and lateral radiographs of the involved extremity are necessary for the diagnosis. If the fracture is not visible, but there is an altered relationship between the humerus and the radius and ulna or the presence of a posterior fat pad sign, a transphyseal fracture or an occult fracture should be suspected (Fig. 724.11). Imaging studies such as oblique radiographs, CT, MRI, and ultrasonography may be required for further confirmation. Displaced supracondylar fractures may be associated with concomitant neurovascular injury (Fig. 724.12) or, rarely, a compartment syndrome. Ulnar nerve injury is identified by decreased sensation over the cutaneous innervation of the lateral aspects of the hand as well as a motor deficit of abduction and adduction of the fingers. Neurologic injury may also appear in the postoperative period. Careful neurologic examination of the hand before and after is needed to document and treat nerve injury. Most nerve injuries associated with displaced supracondylar fractures are neuropraxias and will resolve in several months.

In general, distal humeral fractures need restoration of anatomic alignment. This is necessary to prevent deformity and to allow for normal growth and development. Closed reduction alone, or in association with percutaneous fixation, is the preferred method. Open reduction is indicated for fractures that cannot be reduced by closed methods, fractures with vascular compromise after closed reduction, open fractures, or interarticular fractures, particularly in older children. Inadequate reductions can lead to loss of motion, cubitus varus, cubitus valgus, and rare nonunion or elbow instability. Elbow stiffness is not as common as in adult fractures but may occur with fractures which are severe or intraarticular.

PROXIMAL HUMERUS FRACTURES

Fractures of the proximal humerus account for <5% of fractures in children. They usually result from a fall onto an outstretched arm or direct trauma. The fracture pattern tends to vary with the age group. Physeal and metaphyseal fractures are both common. Among physeal fractures of the proximal humerus, children younger than 5 years of age most commonly have SH I injuries, those 5–10 years of age have metaphyseal fractures, and children older than 11 years of age have SH II injuries. Examination includes a thorough neurologic evaluation, especially of the axillary nerve. The diagnosis is made on AP radiographs of the shoulder. An axillary view is obtained to rule out

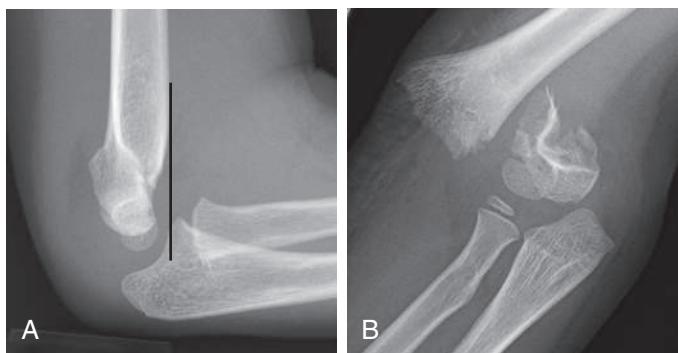


Fig. 724.11 Supracondylar humerus fracture. A, Lateral radiograph of the elbow demonstrates a type II supracondylar humerus fracture, with disruption of the anterior humeral line (black line). This line normally passes through the middle third of the capitellum. Here the capitellum is displaced behind the line. A large joint effusion is noted. B, Anteroposterior radiograph of the elbow shows a type III supracondylar humerus fracture. There is no cortical continuity and significant displacement and overlap of fracture fragments. (From Walters MM, Robertson RL, eds. *Pediatric Radiology: The Requisites*, 4th ed. Philadelphia: Elsevier; 2017: Fig. 7.97.)

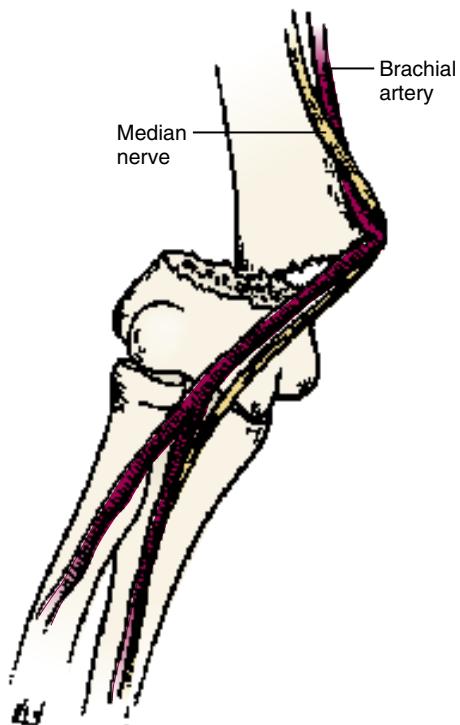


Fig. 724.12 Posterolaterally displaced type III (extension-type) supracondylar humeral fracture. The proximal fragment displaces anteromedially, thus placing the brachial artery and median nerve at risk. (From Ho C. Upper extremity injuries. In: Herring JA, ed. *Tachdjian's Pediatric Orthopaedics*, 6th ed. Philadelphia: Elsevier; 202: Fig. 29.30, p. 1194.)

any dislocation, whereas a scapular-Y view or an axillary view assesses angular deformity in an orthogonal plane. Many children are too uncomfortable to tolerate an axillary view; thus, in this case, a Velpau axillary can be obtained while the arm remains in a sling. SH I injuries do not require reduction because they have excellent remodeling capacity, and simple immobilization in a sling for 2-3 weeks is sufficient. Metaphyseal fractures usually do not need reduction unless the angulation is >50 degrees. In general, sling immobilization is all that is required. SH II fractures with <30 degrees of angulation and <50% displacement are managed in a sling. Displaced fractures are treated

with closed reduction and further stabilization if unstable. Occasionally, open reduction is required because of button-holing of the fracture spike through the deltoid or interposition of the tendon of biceps. The majority of longitudinal growth (80%) of the limb comes from the proximal humeral physis. Additionally, the glenohumeral joint is capable of a large amount of motion. As such, this area is extremely tolerant to deformity. Indications for open reduction are rare. However, as adolescents approach adulthood, these fractures will remodel less.

CLAVICULAR FRACTURES

Neonatal fractures occur as a result of direct trauma during birth, most often through a narrow pelvis or following shoulder dystocia. They can be missed initially and can appear with pseudoparalysis. Childhood fractures are usually the result of a fall on the affected shoulder or direct trauma to the clavicle. The most common site for fracture is the junction of the middle and lateral third clavicle. Tenderness over the clavicle will make the diagnosis. A thorough neurovascular examination is important to diagnose any associated brachial plexus injury. Biceps function is critical to assess, as it is a prognostic indicator for future function.

An AP radiograph of the clavicle demonstrates the fracture and can show overlap of the fragments. Physeal injuries occur through the medial or lateral growth plate and are sometimes difficult to differentiate from dislocations of the acromioclavicular or sternoclavicular joint. Further imaging such as a CT scan may be necessary to further define the injury. Posterior medial clavicular physeal injuries are particularly problematic due to their proximity to the great vessels and the trachea. Closed versus open reduction with a cardiac/thoracic team on standby is necessary. This can be delayed if there is no sign of vascular or respiratory compromise.

The treatment of most clavicle fractures consists of an application of a figure-of-8 clavicle strap or a simple sling. A figure-of-8 strap will extend the shoulders and minimize the amount of overlap of the fracture fragments. Evidence exists for adults that fractures that are shortened or displaced result in strength loss of the shoulder without anatomic reduction and fixation. Many centers are extending that indication to older adolescents; however, a 2019 report suggests similar satisfaction and outcomes with less complications in nonoperatively treated adolescent clavicle fractures when compared with operatively treated injuries. If a fracture is open, tenting the skin, or resulting in neurovascular compromise, surgery is indicated. The physeal fractures are treated with simple sling immobilization without any reduction attempt. Often, anatomic alignment is not achieved, nor is it necessary. Clavicle fractures heal rapidly, typically in 3-6 weeks. A palpable mass of callus is usually visible in thin children, and this remodels satisfactorily in 6-12 months. Complete restoration of shoulder motion and function is uniformly achieved.

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724.4 Lower Extremity Fractures

Jason B. Anari, Alexandre Arkader, and Lawrence Wells

HIP FRACTURES

Hip fractures in children account for <1% of all pediatric fractures. These injuries result from high-energy trauma and can be associated with injury to the chest, head, or abdomen. Treatment of hip fractures in children is associated with a complication rate of up to 60%, including an overall avascular necrosis rate of 50% and a malunion rate of up to 30%. The unique blood supply to the femoral head accounts for the high rate of avascular necrosis. Fractures are classified by the Delbet classification as transphyseal separations, transcervical fractures, cervicotrochanteric fractures, and intertrochanteric fractures. The management principles include urgent anatomic reduction (either open or closed), stable internal fixation (avoiding the physis if possible), and

spica casting if the child is younger. Urgent management has been associated with a lower rate of avascular necrosis and superior overall outcomes. Capsular decompression also has been advocated as decreasing overall pressure on the epiphyseal vessels and has been demonstrated experimentally; the clinical results, however, remain mixed.

FEMORAL SHAFT FRACTURES

Fractures of the femur in children are common. All age groups, from early childhood to adolescence, can be affected. The mechanism of injury varies from low-energy twisting type injuries to high-velocity injuries in vehicular accidents. *Femur fractures in children younger than age 2 years should raise concern for child abuse.* A thorough physical examination is necessary to rule out other injuries and assess the neurovascular status. In the case of high-energy trauma, any signs of hemodynamic instability should prompt the examiner to look for other sources of bleeding. AP and lateral radiographs of the femur demonstrate the fracture. An AP radiograph of the pelvis is obtained to rule out any associated pelvic fracture. Treatment of shaft fractures varies with the age group, as described in Table 724.3.

PROXIMAL TIBIA FRACTURES

Proximal tibia fractures can be physeal injuries, metaphyseal injuries, or avulsion injuries of the tibial spine or tubercle. Physeal injuries can be either isolated or as part of tibial tubercle fracture. If the distal segment is displaced posteriorly the trifurcation of the popliteal vessels may be involved. Careful neurovascular examination is warranted both pre- and postreduction. Anatomic reduction and pin fixation is preferred with unstable fractures or displaced SH III or IV fractures.

Proximal tibial metaphyseal fractures, or the Cozen fracture, are most common in the 3- to 6-year-old age group. They may result in a late valgus deformity even if anatomically reduced. This deformity tends to remodel within 1-2 years but can cause great distress to parents and treating clinicians.

Tibial eminence fractures are fractures of the bony prominence that is the attachment of the anterior cruciate ligament. The mechanism of injury is similar to an anterior cruciate ligament tear in an adult. Displaced fractures require surgical reduction and fixation. This may be done either open or arthroscopically.

Tibial tubercle fractures are common in patients with Osgood-Schlatter syndrome. Care must be taken to observe for compartment syndrome as the injury is associated with injury of the recurrent anterior tibial artery. The injury may be treated nonoperatively if the fracture is displaced <2 mm and the patient has no extensor lag (rare). Open reduction and internal fixation is preferred otherwise.

TIBIA AND FIBULA SHAFT FRACTURES

The tibia is the most commonly fractured bone of the lower limb in children. This fracture generally results from a direct injury. Most tibial fractures are associated with a fibular fracture, and the mean age of presentation is 8 years. The child presents with pain, swelling, and deformity of the affected leg and is unable to bear weight. Distal neurovascular examination is important in assessment. The AP and lateral radiographs should include the knee and ankle. Closed reduction and immobilization are the standard method of treatment. Most

fractures heal well, and children usually have excellent results. Open fractures need to undergo irrigation and debridement as well as antibiotic treatment. The tibia is a subcutaneous bone, so if severe soft tissue loss occurs with an open fracture, the patient may need plastic surgery consultation. Definitive external fixation versus internal fixation and simultaneous soft tissue coverage are alternative treatment strategies to minimize infection. Tibia fractures are associated with compartment syndrome. Vigilance is necessary to avoid disastrous outcomes associated with missed compartment syndrome. *Emergent fasciotomy is indicated as soon as compartment syndrome is diagnosed.* Several return trips to the operating room are often necessary to close, versus cover, the fasciotomy wounds.

TODDLER FRACTURES

Toddler fractures occur in young ambulatory children. The age range for this fracture is typically around 1-4 years (Fig. 724.13). The injury often occurs after a seemingly harmless twist or fall and is often unwitnessed. It is a result of a torsional injury. The children in this age group are usually unable to articulate the mechanism of injury clearly or to describe the area of injury well. The radiographs may show no fracture; in these cases, the diagnosis is made by physical examination. The classic symptom is refusal to bear weight, which can manifest as pulling up the affected extremity or florid display of protest. The other common sign is point tenderness at the fracture site. The AP and lateral views of the tibia-fibula might show a nondisplaced spiral fracture of the distal tibial metaphysis. An oblique view is often helpful because the fracture line may be visible in only one of the three views. Often the fracture

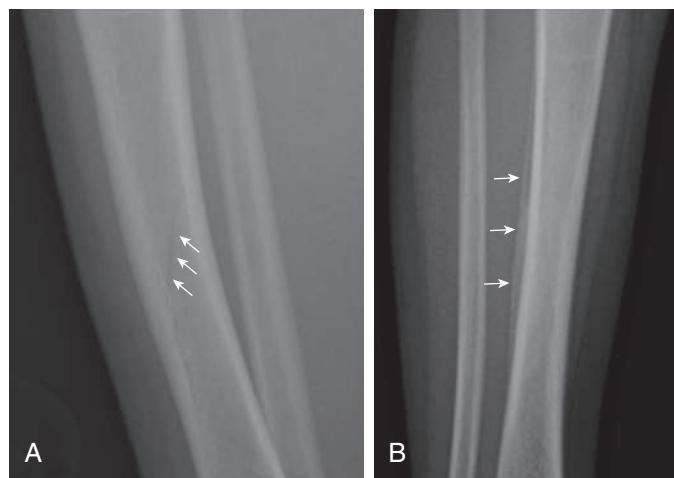


Fig. 724.13 Toddler's fracture of the tibia in a 2-yr-old child presenting with a limp and no history of trauma. A, Lateral radiograph of the lower leg shows a subtle, nondisplaced, oblique fracture through the tibial shaft (arrows). B, Anteroposterior radiograph obtained 10 days later shows healing, with subperiosteal new bone formation along the tibial shaft (arrows). (From Walters MM, Robertson RL, eds. *Pediatric Radiology: The Requisites*, 4th ed. Philadelphia: Elsevier; 2017: Fig. 7.117, p. 256.)

Table 724.3 | Femoral Shaft Fracture: Treatment Options by Age

TREATMENT OPTIONS	0-2 YR	3-5 YR	6-10 YR	>11 YR
Spica cast	x	x		
Traction and spica cast		x	x	x
Intramedullary rod	x	x	x	x
External fixator	x*	x*	x*	x*
Screw or plate	x	x	x	x

*Open fracture.

Modified from Wells L. Trauma related to the lower extremity. In: Dormans JP, ed. *Pediatric Orthopaedics: Core Knowledge in Orthopaedics*. Philadelphia: Mosby; 2005:93.

line is not visualized until 2–3 weeks later, when periosteal reaction and resorption at the fracture site allow better visualization. Inflammatory markers may be ordered to rule out infectious processes if the diagnosis is in doubt. Bone scans were employed in the past but impart a large amount of radiation to the child. The fracture can be safely treated with a below-knee cast or a controlled ankle motion (CAM) walking boot for approximately 3 weeks.

TRIPLANE AND TILLAUX FRACTURES

Triplane and Tillaux fracture patterns occur at the end of the growth period and are based on relative strength of the bone-physis junction and asymmetric closure of the tibial physis. The triplane fractures are so named because the injury has coronal, sagittal, and transverse components (Fig. 724.14). The Tillaux fracture is an avulsion fracture of the anterolateral aspect of the distal tibial epiphysis. Radiographs and further imaging with CT and three-dimensional reconstructions are necessary to analyze the fracture geometry. The triplane fracture involves the articular surface and hence anatomic reduction is necessary. The reduction is further stabilized with internal fixation. The Tillaux fracture is treated by closed reduction. Open reduction is recommended if a residual intraarticular step-off persists.

METATARSAL FRACTURES

Metatarsal fractures are common in children. They usually result from direct trauma to the dorsum of the foot. High-energy trauma or multiple fractures of the metatarsal base are associated with significant swelling. A high index for compartment syndrome of the foot must be maintained and compartment pressures must be measured if indicated. Diagnosis is obtained by AP, lateral, and oblique radiographs of the foot. Most metatarsal fractures can be treated by closed methods in a below-knee cast or walking boot. Weight-bearing is allowed as tolerated. The Jones fracture of the proximal fifth metatarsal is an exception as it lies at a watershed area of vascular supply and thus has an increased risk of nonunion. Patients with Jones fractures should initially be non-weightbearing and should be referred to an orthopedics specialist. Displaced fractures can require closed or open reduction with internal fixation. Percutaneous, smooth Kirschner wires (K-wires) generally provide sufficient internal fixation for these injuries.

TOE PHALANGEAL FRACTURES

Fractures of the lesser toes are common and are usually secondary to direct blows. They commonly occur when the child is barefoot. The toes are swollen, ecchymotic, and tender. There may be a mild deformity. Diagnosis is made radiographically. Bleeding suggests the possibility of an open fracture. The lesser toes usually do not require closed reduction unless significantly displaced. If necessary, reduction can usually be accomplished with longitudinal traction on the toe. Casting is not usually necessary. Buddy taping of the fractured toe to an adjacent stable toe usually provides satisfactory alignment and relief of symptoms. Crutches and heel walking may be beneficial for several days until the soft tissue swelling and the discomfort decrease.

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724.5 Operative Treatment of Fractures

Jason B. Anari, Alexandre Arkader, and Lawrence Wells

Surgery is required for 4–5% of pediatric fractures. The common indications for operative treatment in children and adolescents include displaced physeal fractures, displaced intraarticular fractures, unstable fractures, multiple injuries, open fractures, failure to achieve adequate reduction in older children, failure to maintain an adequate reduction, and certain pathologic fractures.

The aim of operative intervention is to obtain anatomic alignment and relative stability. Rigid fixation is not necessary as it is in adults for early mobilization. The relatively stable construct can be supplemented

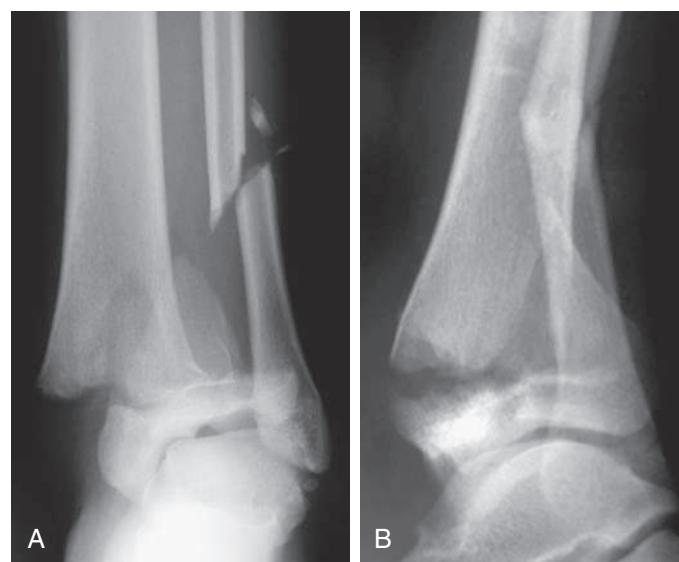


Fig. 724.14 The triplane fracture is a transitional fracture: anteroposterior (A) and lateral (B) radiographs. (From Dormans JP. *Pediatric Orthopedics: Introduction to Trauma*. Philadelphia: Mosby; 2005:38.)

Table 724.4 Common Indications for External Fixation in Pediatric Fractures

Grades II and III open fractures
Fractures associated with severe burns
Fractures with soft tissue loss requiring free flaps or skin grafts
Fractures requiring distractions such as those with significant bone loss
Unstable pelvic fractures
Fractures in children with associated head injuries and spasticity
Fractures associated with vascular or nerve repairs or reconstruction

with external immobilization such as a cast, splint, or CAM walking boot. SH types III and IV injuries require anatomic alignment, and if they are unstable, internal fixation is used (smooth K-wires, preferably avoiding the course across the growth plate). Multiple closed reductions of an epiphyseal fracture are contraindicated because they can cause permanent damage to the physis.

SURGICAL TECHNIQUES

It is important to take great care with soft tissues and skin. The other indications for open reduction and internal fixation are unstable fractures of the spine, ipsilateral fractures of the femur and tibia, neurovascular injuries requiring repair, and open fractures. Closed reduction and minimally invasive fixation are specifically used for supracondylar fractures of the distal humerus and most phalangeal fractures. Failure to obtain anatomic alignment by closed means is an indication for an open reduction. Percutaneous techniques such as intramedullary fixation and minimally invasive plate osteosynthesis are increasingly popular as well.

As children become older, surgical techniques become more similar to adult techniques. The classic example of this is the femoral shaft fracture. Newborns may be treated with a soft dressing or Pavlik harness; young children may have a spica cast; older children will often be treated with flexible nails. Adolescents will frequently be treated with rigid intramedullary fixation similar to their adult counterparts.

Table 724.4 summarizes the main indications for external fixation. The advantages of external fixation include rigid immobilization of the fractures, access to open wounds for continued management, and easier patient mobilization for treatment of other injuries and transportation for diagnostic and therapeutic procedures. The majority of

complications with external fixation are pin tract infections, chronic osteomyelitis, and refractures after pin removal.

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724.6 Complications of Fractures in Children

Jason B. Anari, Alexandre Arkader, and Lawrence Wells

Complications of fractures in children can be categorized as (1) complications of the injury itself, (2) complications of treatment, and (3) late complications resulting from growth disturbance or deformity.

COMPLICATIONS RESULTING FROM INJURY

Growth arrest is possible in phyeal fractures, particularly widely displaced phyeal fractures about the distal femur, proximal tibia, or distal ulna. Fractures about the hip may cause **avascular necrosis** or premature phyeal closure, particularly when the fracture involves the proximal femoral physis. Unacceptable alignment may cause loss of motion or limb malalignment. Fracture malunion may cause cosmetically unappealing bumps or curves in the limb, and at times functional impairment. **Compartment syndrome** can occur, particularly in diaphyseal tibia fractures or high energy or open both bone forearm fractures. Supracondylar humerus fractures, distal femur fractures, and proximal tibia fractures may result in neurovascular compromise. Nonunions are rare in children but can be seen with intraarticular fractures, such as distal humerus lateral condyle fractures. Malunions or missed Monteggia fracture dislocations about the elbow can cause permanent stiffness and loss of function if the deformity is not corrected. Displaced intraarticular fractures can result in posttraumatic arthritis and early joint degeneration. Open fractures can result in infection and osteomyelitis if inadequately treated. Older children with severe injuries of the lower extremity can be vulnerable to **deep vein thrombosis**.

COMPLICATIONS OF TREATMENT

Treatment may complicate fractures. Cast immobilization can result in **cast ulcers**, either from inadequate padding of bony prominences or from patients placing objects in the cast. Casts that are too tight can cause neurovascular compromise and compartment syndrome. Patients can get cast saw burns from using cast saws that are too dull to remove the cast. Safe operation of a cast saw requires monitoring of blade temperature. The saw blade should be intermittently cooled by taking a break to avoid overheating and thermal injury to the skin. Improperly placed casts can promote fracture displacement and malunion. Surgical treatment can be complicated by blood loss, neurovascular compromise, iatrogenic phyeal damage, and hardware complications such as infection or hardware failure. Symptomatic hardware may require later removal.

LATE COMPLICATIONS OF TRAUMA

Late effects of trauma can be from partial or complete closure of the physis or malunion of the fracture. This can lead to limb angular deformity, shortening, or incongruency. Angular deformities can be treated by hemiepiphiodesis or osteotomy. Joint incongruency may be a very difficult problem to deal with and may ultimately lead to early degenerative joint disease. Reflex sympathetic dystrophy is another poorly understood late effect of trauma but can be debilitating. Distal radius fractures have an above average rate of reflex sympathetic dystrophy relative to other injuries. Physical and occupational therapists are very helpful in managing this condition. Limited evidence exists that vitamin C may be useful in the acute setting of high-risk injuries to prevent this complication.

Chapter 725

Osteomyelitis

Samir S. Shah

Osteomyelitis, or infection of the bone, may be classified as acute or chronic. These clinical definitions correspond with treatment recommendations. **Acute osteomyelitis** is defined as the diagnosis of bone infection within 4 weeks after onset of clinical signs or symptoms in a previously uninfected bone. **Chronic osteomyelitis** is defined as a protracted and indolent disease process with presence of a sequestrum or relapse of infection at the same site following apparently successful treatment; sequestra may arise as a complication of treated or untreated acute hematogenous osteomyelitis.

ETIOLOGY

Bacteria are the most common pathogens in acute skeletal infections. *Staphylococcus aureus* (see Chapter 227.1) is the most common infecting organism in osteomyelitis among all age groups, including newborns. The prevalence of community-acquired methicillin-resistant *S. aureus* (CA-MRSA) as a cause of osteomyelitis varies substantially by region.

Group B streptococcus (see Chapter 230) and gram-negative enteric bacilli (*Escherichia coli*, see Chapter 246) are prominent pathogens in neonates; group A streptococcus (see Chapter 229) constitutes <10% of all cases in this group. After 6 years of age, most cases of osteomyelitis are caused by *S. aureus*, group A streptococci, or *Pseudomonas aeruginosa* (see Chapter 251.1). Cases of *Pseudomonas* infection are related almost exclusively to puncture wounds of the foot, with direct inoculation of *P. aeruginosa* from the foam padding of the shoe into bone or cartilage, which develops as osteochondritis. *Salmonella* spp. (see Chapter 244) and *S. aureus* are the two most common causes of osteomyelitis in children with sickle cell disease (see Chapter 511.1). *Streptococcus pneumoniae* (see Chapter 228) most commonly causes osteomyelitis in children younger than 24 months of age and in children with sickle cell disease, but its frequency has declined because of pneumococcal conjugate vaccines. *Bartonella henselae* (see Chapter 255) can cause osteomyelitis of any bone but is most often seen in pelvic and vertebral bones.

Kingella kingae (see Chapter 239) is the second most common cause of osteomyelitis in children younger than 4 years of age. The organism causes osteomyelitis, spondylodiscitis, and septic arthritis (see Chapter 726) in this age group, especially when there is a subacute presentation. *K. kingae* can be difficult to detect unless polymerase chain reaction (PCR) testing is used.

Infection with atypical mycobacteria (see Chapter 263), *S. aureus*, or *Pseudomonas* can occur after penetrating injuries. These organisms, as well as coagulase-negative staphylococci or gram-negative enteric bacteria, may cause bone infection related to implanted materials such as orthopedic hardware. Fungal infections usually occur as part of multi-system disseminated disease; *Candida* (see Chapter 280) osteomyelitis sometimes complicates fungemia in neonates with or without indwelling vascular catheters. Blastomycosis causes multiple bone lesions in endemic areas.

EPIDEMIOLOGY

The median age of children with musculoskeletal infections is approximately 6 years. Bone infections are more common in males than females.

Minor closed trauma is a common preceding event in cases of osteomyelitis, occurring in approximately 30% of patients. Impaired host defenses (e.g., hemoglobinopathies, human immunodeficiency virus, or chronic granulomatous disease) also increase the risk of skeletal infection. Table 725.1 lists other risk factors.

Table 725.1 Microorganisms Isolated from Patients with Osteomyelitis and Their Clinical Associations

MOST COMMON CLINICAL ASSOCIATION	MICROORGANISM
Frequent microorganism in any type of osteomyelitis	<i>Staphylococcus aureus</i> (susceptible or resistant to methicillin)
Associated with septic arthritis, spondylodiscitis, long or unusual bones, age <4 yr, mild symptoms	<i>Kingella kingae</i>
Foreign body-associated infection	Coagulase-negative staphylococci, other skin flora, atypical mycobacteria, fungi
Common in nosocomial infections	<i>Enterobacteriaceae</i> , <i>Pseudomonas aeruginosa</i> , <i>Candida</i> spp.
Decubitus ulcer or ulceration associated with sensory autonomic neuropathies	<i>S. aureus</i> , streptococci, gram-negative enterics, and/or anaerobic bacteria; polymicrobial infections are common
Sickle cell disease	<i>Salmonella</i> spp., <i>S. aureus</i> , or <i>Streptococcus pneumoniae</i>
Exposure to kittens	<i>Bartonella henselae</i>
Human or animal bites	<i>Pasteurella multocida</i> or <i>Eikenella corrodens</i>
Immunocompromised patients	<i>Aspergillus</i> spp., <i>Candida albicans</i> , or <i>Mycobacteria</i> spp.
Populations in which tuberculosis is prevalent	<i>Mycobacterium tuberculosis</i>
Populations in which these pathogens are endemic	<i>Brucella</i> spp., <i>Coxiella burnetii</i> , fungi found in specific geographic areas (coccidioidomycosis, blastomycosis, histoplasmosis)

Modified from Lew DP, Waldvogel FA. Osteomyelitis. *Lancet*. 2004;364:369–379.

PATHOGENESIS

Bacteria reach bone matrices most commonly via hematogenous spread (primary bacteremia). Less common mechanisms include direct inoculation (i.e., trauma or procedures) or contiguous spread from infection of adjacent sites such as synovial fluid or soft tissues.

The unique anatomy and circulation of the ends of long bones result in the predilection for localization of bloodborne bacteria. In the metaphysis, nutrient arteries branch into non-anastomosing capillaries under the physis, which make a sharp loop before entering venous sinusoids draining into the marrow. Low-velocity blood flow in this area predisposes to bacterial invasion. Once a bacterial focus is established, phagocytes migrate to the site and produce an inflammatory exudate (metaphyseal abscess). The generation of proteolytic enzymes, toxic oxygen radicals, and cytokines results in decreased oxygen tension, decreased pH, osteolysis, and tissue destruction. As the inflammatory exudate progresses, pressure increases spread through the porous metaphyseal space via the Haversian system and Volkmann canals into the subperiosteal space. Purulence beneath the periosteum may lift the periosteal membrane of the bony surface, further impairing blood supply to the cortex and metaphysis.

In newborns and young infants, transphyseal blood vessels connect the metaphysis and epiphysis, so it is common for pus from the metaphysis to enter the joint space. This extension through the physis

has the potential to result in abnormal growth and bone or joint deformity. During the latter part of the first year of life, the physis forms, obliterating the transphyseal blood vessels. Joint involvement can occur where the metaphysis is intraarticular (hip, ankle, shoulder, and elbow), and subperiosteal pus ruptures into the joint space.

In later childhood, the periosteum becomes more adherent, favoring pus to decompress through the periosteum. Once the growth plate closes in late adolescence, hematogenous osteomyelitis more often begins in the diaphysis and can spread to the entire intramedullary canal. Septic arthritis contiguous with a site of osteomyelitis is also seen in older children with *S. aureus* osteomyelitis, which may be related to simultaneous hematogenous inoculation of bone and joint space. Septic arthritis may also result from infected material entering the synovial space from an adjacent osteomyelitis.

CLINICAL MANIFESTATIONS

The earliest signs and symptoms of acute osteomyelitis, often subtle and nonspecific, generally depend on patient age. Neonates might exhibit *pseudoparalysis* or pain with movement of the affected extremity (e.g., diaper changes). Half of neonates do not have fever and might not appear ill. Older infants and children are more likely to have pain, fever, and localizing signs such as edema, erythema, and warmth. With involvement of the lower extremities, limp or refusal to walk is seen in approximately half of patients.

Focal tenderness over a long bone can be an important finding. Local swelling and redness with osteomyelitis suggests spread of infection beyond the metaphysis and into the subperiosteal space, representing a secondary soft tissue inflammatory response. Pelvic osteomyelitis can manifest with subtle findings such as hip, thigh, groin, or abdominal pain. Vertebral osteomyelitis typically presents as back pain with or without tenderness to palpation over the vertebral processes (Chapter 720.7).

Long bones are principally involved in osteomyelitis (Table 725.2); the femur and tibia are equally affected and together constitute almost half of all cases. The bones of the upper extremities account for 25% of all cases. Flat bones are less commonly affected.

Usually, a single site of bone or joint is involved, although multifocal osteomyelitis may be noted in up to 20% of children with *S. aureus* infections. In neonates, two or more bones are involved in almost half of the cases. Multifocal disease may also be seen with tuberculosis, cat-scratch disease, and brucellosis. Clinical manifestations of chronic infection are more indolent, and fever is unusual. Children with *subacute* symptoms and focal findings in the metaphyseal area (usually of the tibia) might have a **Brodie abscess**, with a well-defined radiographic lucency and surrounding reactive bone. The contents of Brodie abscesses are often sterile, but *S. aureus* is often the most common pathogen (Fig. 725.1).

Some patients with osteomyelitis due to *S. aureus* infection develop a deep venous thrombosis adjacent to the affected bone that can produce septic pulmonary emboli; these patients are often critically ill. Uncomplicated disease should be distinguished from more complicated osteomyelitis (Table 725.3).

DIAGNOSIS

The diagnosis of osteomyelitis begins with clinical suspicion and requires appropriate cultures and imaging studies. *Blood cultures should be performed in all suspected cases before administration of antibiotic therapy*. Blood cultures are positive in ~30% of patients. Blood culture contamination rates are low, generally <5%; microbes such as coagulase-negative staphylococci, α -streptococci (except *S. pneumoniae* and *S. anginosus* group), *Bacillus* species, *Corynebacterium*, and *Cutibacterium* are usually considered contaminants when identified in blood culture from a patient with acute or subacute hematogenous osteomyelitis.

Depending on the results of imaging studies, aspiration or biopsy of bone or subperiosteal abscess for Gram stain, standard bacterial culture, PCR for *K. kingae*, and possibly bone histology provides the optimal specimen for culture to confirm the diagnosis and significantly increases the yield compared with blood culture alone. These specimens, which identify a causative bacteria in ~60% of cases, are often obtained by the interventional radiologist or at the time of surgical

Table 725.2 Site of Involvement in Acute Hematogenous Osteomyelitis	
SITE	%
TUBULAR BONE	
Femur	25
Tibia	24
Humerus	13
Phalanges	5
Fibula	4
Radius	4
Ulna	2
Metatarsal	2
Clavicle	0.5
Metacarpal	0.5
CUBOIDAL BONE	
Calcaneus	5
Talus	0.8
Carpals	0.5
Cuneiform	0.5
Cuboid	0.3
IRREGULAR BONE	
Ischium	4
Ilium	2
Vertebra	2
Pubis	0.8
Sacrum	0.8
FLAT BONE	
Skull	1
Rib	0.5
Sternum	0.5
Scapula	0.5
Maxilla	0.3
Mandible	0.3

Data from Krogstad P. Osteomyelitis. In: Cherry JD, Harrison GJ, Kaplan SL, et al., eds. *Feigin and Cherry's Textbook of Pediatric Infectious Diseases*, 8th ed. Philadelphia: Elsevier, 2019. Table 55.2.

drainage by the orthopedic surgeon. Direct inoculation of clinical specimens into aerobic blood culture bottles can improve the recovery of *K. kingae*, particularly if held for 1 week. PCR is the most sensitive technique to detect *K. kingae*, even up to 6 days after antibiotics are initiated. Anaerobic, fungal, and mycobacterial cultures may be performed if risk factors are identified by history or physical examination.

There are no specific laboratory tests for osteomyelitis. Laboratory evaluation of children with suspected osteomyelitis may include a complete blood count and C-reactive protein (CRP). A complete blood count may contribute to assessment of infection severity (e.g., anemia, thrombocytopenia) and suggest an alternative diagnosis (e.g., hematologic malignancy). The initial CRP is elevated in most children with acute osteomyelitis. CRP is nonspecific and does not establish the diagnosis of osteomyelitis, but serial monitoring of an elevated CRP may be of value in assessing response to therapy or identifying complications. Erythrocyte sedimentation rate (ESR) is no longer routinely recommended in cases of acute hematogenous osteomyelitis. Data on procalcitonin are insufficient.

RADIOGRAPHIC EVALUATION

Radiographic studies play a crucial role in the evaluation of osteomyelitis. Conventional radiographs and MRI are the primary modalities. Ultrasonography, CT, and radionuclide studies can also contribute to establishing the diagnosis in selected cases.

Plain Radiographs

Within 72 hours of onset of symptoms of osteomyelitis, plain radiographs of the involved site using soft tissue technique and compared with the opposite extremity, if necessary, can show displacement of the deep muscle planes from the adjacent metaphysis caused by deep-tissue edema. Lytic bone changes are not visible on radiographs until 30–50% of the bony matrix is destroyed. Tubular long bones do not show lytic changes for 7–14 days after onset of infection. Infection in flat and irregular bones can take longer to appear. Radiographs in children with possible osteomyelitis are important to exclude other possible causes (e.g., fracture) of the presenting symptoms and signs.

Magnetic Resonance Imaging and Computed Tomography

MRI is more sensitive than CT or radionuclide imaging in acute osteomyelitis and is the best radiographic imaging technique for identifying abscesses and for differentiating between bone and soft tissue infection. MRI provides precise anatomic detail of subperiosteal pus and accumulation of purulent debris in the bone marrow and metaphyses for possible surgical intervention. In acute osteomyelitis, purulent debris and edema appear dark, with decreased signal intensity on T1-weighted images, with fat appearing bright (Figs. 725.2 and 725.3). The opposite is seen in T2-weighted images. The signal from fat can be diminished with fat-suppression techniques to enhance visualization. Gadolinium administration can also enhance MRI. Cellulitis and sinus tracts appear as areas of high signal intensity on T2-weighted images. Short tau inversion recovery (STIR) MRI is a rapid imaging modality for osteomyelitis (Fig. 725.4). MRI can also demonstrate contiguous or isolated septic arthritis, pyomyositis, or venous thrombosis. *Whole body rapid STIR MRI is an effective alternative to radionuclide imaging where multiple sites of infection are suspected or the site of infection cannot be clearly localized on exam.* CT can demonstrate osseous and soft tissue abnormalities and is ideal for detecting gas in soft tissues but has poor sensitivity for detecting the presence of osteomyelitis.

Radionuclide Studies

Radionuclide imaging, an alternative to MRI, may be useful if multiple foci are suspected. Technetium-99 (^{99m}Tc) methylene diphosphonate, which accumulates in areas of increased bone turnover, is the preferred agent for radionuclide bone imaging (three-phase bone scan). Any areas of increased blood flow or inflammation can cause increased uptake of ^{99m}Tc in the first and second phases, but osteomyelitis causes increased uptake of ^{99m}Tc in the third phase (4–6 hours). Three-phase imaging with ^{99m}Tc has excellent sensitivity (84–100%) and specificity (70–96%) in hematogenous osteomyelitis and can detect osteomyelitis within 24–48 hours after onset of symptoms. The sensitivity in neonates is much lower because of poor bone mineralization. Advantages include infrequent need for sedation and the ability to image the entire skeleton for detection of multiple foci. Disadvantages include exposure to radiation, inability to image surrounding soft tissues, and overall lack of detail, which limits the tests' utility for preoperative planning.

DIFFERENTIAL DIAGNOSIS

Distinguishing osteomyelitis from cellulitis or trauma (unintentional or abuse) may be difficult, particularly when the history is limited. Myositis or pyomyositis can also appear similar to osteomyelitis with fever, warm and swollen extremities, and limping; tenderness to palpation of the affected soft tissue area is generally more diffuse than noted in acute osteomyelitis. Myositis and pyomyositis may be isolated but are often found adjacent to an osteomyelitis on MRI. **Pyomyositis** is most often caused by *S. aureus*, followed by group A streptococcus. The pelvic muscles are a common site of pyomyositis and can mimic a pelvic osteomyelitis. MRI is the definitive

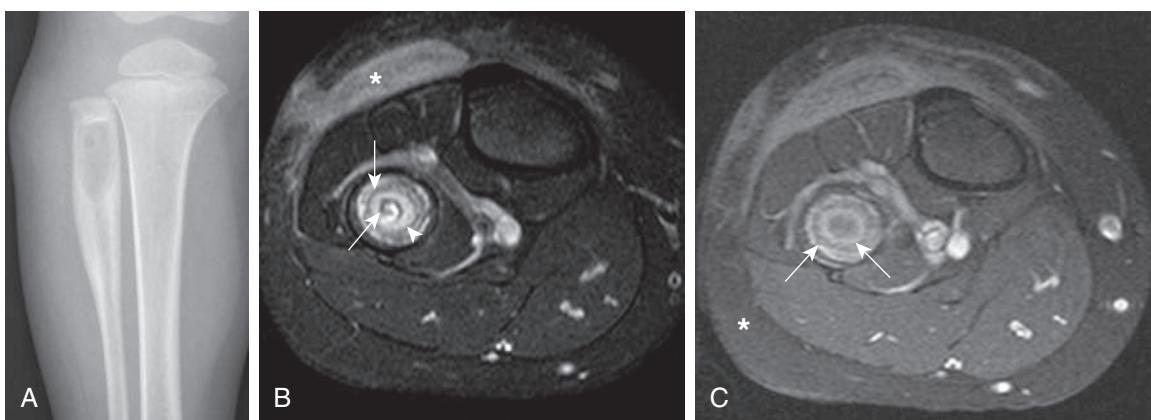


Fig. 725.1 A, Radiograph demonstrates a lytic lesion in the proximal fibula with laminated thick periostitis. Axial T2-weighted fat-saturated MR image (B) shows a layered appearance with intermediate signal (arrowhead) between inner and outer rims of lower signal intensity (arrows) and a more central hyperintense region. Also note the soft tissue phlegmon/early abscess formation (asterisk). On an axial T1-weighted, fat-saturated, postgadolinium MR image (C), a rim of low signal intensity (outer arrow) surrounds an inner rim of enhancing granulation tissue (inner arrow), which surrounds the nonenhancing abscess. (From Kan JH, Meyers AB, Azouz EM. Musculoskeletal infections. In: Coley BD, ed. *Caffey's Pediatric Diagnostic Imaging*, 13th ed. Philadelphia: Elsevier; 2019: Fig. 137.17.)

Table 725.3 Characteristics of Uncomplicated vs Complicated Osteomyelitis*

CHARACTERISTIC	UNCOMPLICATED	COMPLICATED
Sites of infection	Single bone	Two or more bones involved Additional soft tissue sites of infection beyond the bone (e.g., muscle [myositis or pyomyositis], pneumonia, and liver abscess)
Clinical response to medical and surgical treatment	Rapid (within 3-5 days), including signs of sepsis or septic shock	Slow, prolonged response, or lack of clinical response Need for more than one surgery for source control
Course of bacteremia when present	Rapid resolution of bacteremia (serial blood cultures become negative when obtained within 1-2 days after the initiation of therapy and source control)	Prolonged bacteremia (3 or more days), suggestive of uncontrolled infection/distant site(s) of infection
Acute sequelae of infection	None	Venous thrombosis or septic thrombophlebitis Endocarditis
Late sequelae of infection	No findings that suggest risk of physeal injury or other short- or long-term osteoarticular sequelae of infection	Findings concerning for physeal injury with potential impacts on bone growth with long-term sequelae Presence of or concern for pathologic fracture

*This set of criteria is consensus based with primary focus on clinical findings and course. It may be reasonable to include additional laboratory tests such as the serum C-reactive protein (CRP) in making a determination of an uncomplicated vs complicated course. Concepts such as (1) rapid fall of the CRP concentration within 48 hr of initiation of treatment or (2) a 50% or more decline from peak CRP concentration within 3-5 days of admission or first surgical debridement may be considered. Further research into the various components and functionality of this definition, and any added utility of the CRP or other laboratory markers, will have value and is encouraged.

From Woods CR, Bradley JS, Chatterjee A, et al. Clinical practice guideline by the Pediatric Infectious Diseases Society of America: 2021 guideline on diagnosis and management of acute hematogenous osteomyelitis in pediatrics. *J Pediatric Infect Dis Soc*. 2021;10(8):801-844. Table 1.

study to identify and localize pelvic pyomyositis (Fig. 725.5). An **iliopsoas abscess** can manifest with thigh pain, limp, and fever and must be considered in the differential diagnosis of osteomyelitis. The iliopsoas abscess may be primary (hematogenous: *S. aureus*) or secondary to infection in adjacent bone (*S. aureus*), kidney (*E. coli*) or intestine (*E. coli*, *Bacteroides* spp.). *Mycobacterium tuberculosis* has been reported in patients with HIV infection. Any child with negative x-ray imaging and a negative hip aspiration who presents with fever, limp, and elevated inflammatory markers should be evaluated for pyomyositis.

Appendicitis, urinary tract infection, and gynecologic disease are among the conditions in the differential diagnosis of pelvic osteomyelitis. Children with leukemia commonly have bone pain or joint pain as an early symptom. Neuroblastoma with bone involvement may be mistaken for osteomyelitis. Primary bone tumors need to be considered, but fever and other signs of illness are generally absent except in Ewing sarcoma. In patients with sickle cell disease, distinguishing bone infection from infarction may be challenging.

Chronic recurrent multifocal osteomyelitis (CRMO) (also called chronic nonbacterial osteomyelitis, CNO) is a nonpyrogenic, sterile inflammatory bone disease that is considered an autoinflammatory disorder (see Chapter 204). It may also be associated with a family history of autoimmune disease; the affected patient may have other inflammatory diseases such as Crohn disease, Sweet syndrome, psoriasis, and palmar plantar pustulosis. CRMO in children has many similarities with synovitis, acne, pustulosis, hyperostosis, and osteitis syndrome (SAPHO), seen in adults. CRMO also has similarities to Majeed syndrome, an autosomal recessive disorder with a microcytic dyserythropoietic anemia, and with a deficiency of interleukin-1 receptor antagonist (DIRA), an autosomal recessive autoinflammatory disease.

In contrast to infectious osteomyelitis, CRMO is multifocal, recurrent, and may involve bones not typical of osteomyelitis (spine, pelvis, clavicle, mandible, and calcaneus). Plain radiographs reveal osteolytic lesions or sclerosis; whole body STIR MRI imaging is the diagnostic study of choice (Fig. 725.6).

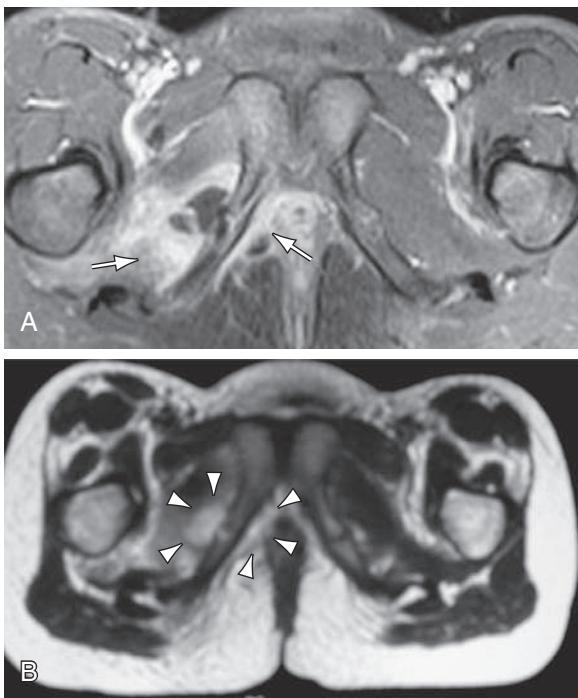


Fig. 725.2 MRI of an 8-year-old female with acute pelvic hematogenous osteomyelitis. **A**, Axial T1-weighted contrast-enhanced MRI with fat saturation reveals a nonenhancing fluid collection adjacent to the inflamed pubic synchondrosis. **B**, The fluid collection appears hyperintense on the corresponding T2-weighted image (arrowheads). In addition, a contrast enhancement within the adjacent internal obturator muscle is seen (arrow), indicating acute pelvic hematogenous osteomyelitis with complicating adjacent abscess formation and soft tissue inflammation. (From Weber-Chrysochoou C, Corti N, Goetschel P, et al. Pelvic osteomyelitis: a diagnostic challenge in children. *J Pediatr Surg*. 2007;42:553–557.)



Fig. 725.4 Coronal STIR MR image demonstrates a salt-and-pepper appearance of marrow edema and periosteal reaction (arrow). (From Kan JH, Azouz EM. Musculoskeletal infections. In: Coley BD, ed. Caffey's Pediatric Diagnostic Imaging, 13th ed. Philadelphia: Elsevier; 2019: Fig. 137.14.)

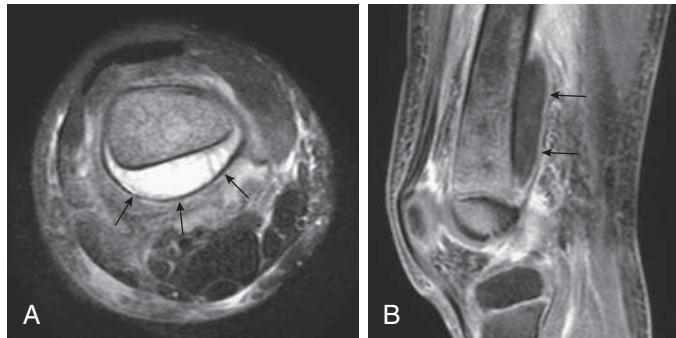


Fig. 725.3 Acute osteomyelitis of the distal femur in a 5-yr-old male. **A**, T2-weighted fat-saturated axial MRI shows a large subperiosteal abscess (arrows) at the posterior aspect of the femur. Increased signal is seen within the bone, and there is adjacent soft tissue edema. **B**, T1-weighted fat-saturated postgadolinium sagittal MRI shows the longitudinal extent of the subperiosteal abscess with enhancing wall (arrows). (From Kan JH, Azouz EM. Musculoskeletal infections. In: Coley BD, ed. Caffey's Pediatric Diagnostic Imaging, 13th ed. Philadelphia: Elsevier; 2019: Fig. 137.13.)

Pain in CRMO is usually insidious and noted at night; fever is not always present. The mean age of onset is 10 years. The CRP may be elevated but is not as high as in bacterial osteomyelitis. Pain usually responds to nonsteroidal antiinflammatory drugs. Second-line treatments include systemic corticosteroids or tumor necrosis factor- α inhibitors.

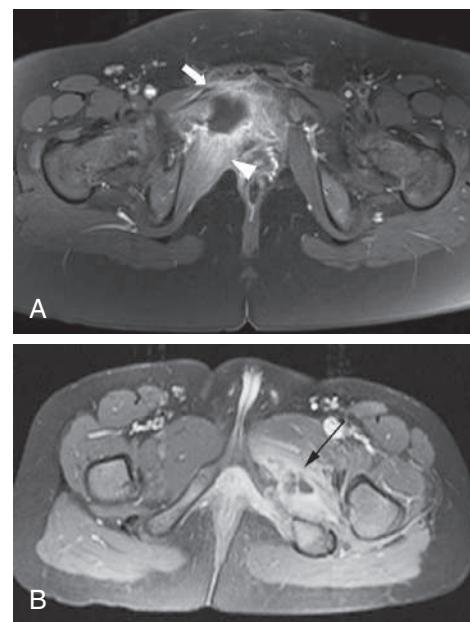


Fig. 725.5 **A**, Pelvic pyomyositis in a 10-yr-old male presenting with limping. Pelvis MRI demonstrates an avid contrast enhancement of the internal obturator muscle (arrowhead) with an abscess on T1-weighted fat-saturated postcontrast axial image (arrow). **B**, Pyomyositis in a 7-yr-old male with left pelvic pain and fever. Axial T1 fat-saturated postcontrast image through the inferior ramus of the obturator ring demonstrates multiloculated, rim-enhancing fluid collections in the adductor muscles (arrow), which is characteristic of pyomyositis. (**A** from Bartoloni A, Gómez A, Pilar M, et al. Imaging of the limping child. *Eur J Radiol*. 2018;109:155–170. Fig 13; **B** from Pruthi S, Thapa MM. Infectious and inflammatory disorders. *Magn Reson Imaging Clin North Am*. 2009;17:423. Fig 7.)



Fig. 725.6 MRI in a patient with chronic recurrent multifocal osteomyelitis. **A**, Whole body image showing multiple foci of osteomyelitis (arrows), some of which are distributed symmetrically. **B**, Image of the ankle showing inflammatory metaphyseal and epiphyseal lesions. **C**, Image of the left femur showing involvement of the diaphysis with a soft tissue reaction. (From Wipff J, Adamsbaum C, Kahan A, Job-Deslandre C. Chronic recurrent multifocal osteomyelitis. *Joint Bone Spine*. 2011;78:555–560. Fig. 3, p. 557.)

TREATMENT

Optimal treatment of skeletal infections requires collaborative efforts of pediatricians, orthopedic surgeons, and interventional radiologists. Obtaining a blood culture *before* antibiotics are given is essential. Most patients with osteomyelitis have an indolent, non-life-threatening condition, and in these circumstances antibiotics may be deferred until a decision about whether to obtain additional diagnostic cultures (periosteal abscess, bone) has been made. A short duration of antibiotic pretreatment (<48 hours) for osteomyelitis caused by *S. aureus* has minimal impact on culture yield from abscess or bone specimens. In critically ill patients, empirical antimicrobial therapy should be initiated without delay.

Antimicrobial Therapy

The initial empirical antimicrobial therapy is based on knowledge of likely bacterial pathogens at various ages, the results of the Gram stain of aspirated material, and additional considerations (Table 725.4). In neonates, an antistaphylococcal penicillin, such as nafcillin or oxacillin (100-200 mg/kg/24 hr divided q6hr IV), and a broad-spectrum cephalosporin, such as cefepime (100-150 mg/kg/24 hr divided q12hr IV), provide coverage for the methicillin-susceptible *S. aureus* (MSSA), group B streptococcus, and gram-negative bacilli. If methicillin-resistant *Staphylococcus* (MRSA) is suspected, clindamycin or vancomycin is substituted for nafcillin. If the neonate is a premature infant or has a central vascular catheter, the possibility of nosocomial bacteria (gram-negative enteric, *Pseudomonas*, or *S. aureus*) or fungi (*Candida* spp.) should be considered. In older infants and children, the principal pathogens are *S. aureus*, *K. kingae*, and group A streptococcus.

Cefazolin (100-150 mg/kg/24 hr divided q6hr IV) or nafcillin (100-200 mg/kg/24 hr divided q6hr) is the agent of choice for parenteral treatment of osteomyelitis caused by MSSA and is the backbone of empirical treatment for acute hematogenous osteomyelitis. A major factor influencing the selection of empirical therapy is the rate of methicillin resistance among community *S. aureus* isolates.

In areas where the prevalence of CA-MRSA is >10–20%, clindamycin (30-40 mg/kg/24 hr divided q6-8hr) or vancomycin (40-60 mg/kg/24 hr divided q6-8hr IV) should be used as empirical treatment. Clindamycin is often preferred over vancomycin when the rate of clindamycin resistance is low among community *S. aureus* isolates given the renal toxicity associated with vancomycin. Because β -lactams are superior to clindamycin and vancomycin for the treatment of MSSA, dual drug therapy in critically ill children should be continued until the causative organism is identified and susceptibilities are known. Rapid molecular diagnostic tests that can accurately differentiate MRSA from MSSA within hours of blood culture positivity can help to avoid prolonged exposure to multiple agents. Clindamycin is the best studied alternative therapy for susceptible isolates of MRSA and for MSSA when a β -lactam cannot otherwise be used.

Penicillin is first-line therapy for treating osteomyelitis caused by susceptible strains of *S. pneumoniae* and all group A streptococci. Cefotaxime or ceftriaxone is recommended for pneumococcal isolates with resistance to penicillin and for most *Salmonella* spp.

Special situations dictate deviations from the usual empirical antibiotic selection. In patients with sickle cell disease with osteomyelitis, gram-negative enteric bacteria (*Salmonella*) are common pathogens, as well as *S. aureus*, so a broad-spectrum cephalosporin such as cefepime (150 mg/kg/24 hr q8hr IV) is used in addition to clindamycin or vancomycin. Clindamycin is a useful alternative drug for patients allergic to β -lactam drugs. In addition to good antistaphylococcal activity, clindamycin has broad activity against anaerobes and is useful for treating infections secondary to penetrating injuries or compound fractures. For immunocompromised patients, combination therapy is usually initiated, such as with vancomycin and ceftazidime, cefepime, or piperacillin-tazobactam, with or without an aminoglycoside. *K. kingae* responds to β -lactam antibiotics, including penicillin and cephalosporins, but some isolates produce a β -lactamase. Thus a first-generation cephalosporin (cefazolin) is a reasonable component of empirical therapy in children younger than 4 years of age. Although

Table 725.4 Antibiotic Choice and Duration of Therapy for Uncomplicated Pediatric Acute Hematogenous Osteomyelitis Caused by *Staphylococcus aureus**,[†]

PATHOGEN	PARENTERAL THERAPY	ORAL CONVALESCENT THERAPY	DURATION [‡]
<i>S. aureus</i> , methicillin susceptible	Preferred: [§] Cefazolin Semisynthetic penicillin, [#] e.g., oxacillin and nafcillin	Preferred: Cephalexin	3-4 weeks if uncomplicated
	Alternatives: [#] Clindamycin Vancomycin Ceftaroline	Alternative: Clindamycin	3-4 weeks if uncomplicated
<i>S. aureus</i> , methicillin resistant, susceptible to clindamycin	Preferred: Clindamycin	Preferred: Clindamycin	3-4 weeks if uncomplicated
	Alternatives: Vancomycin Daptomycin Ceftaroline Linezolid	Alternatives: [¶] Linezolid	No data
<i>S. aureus</i> , methicillin resistant, resistant to clindamycin	Preferred: Vancomycin	Preferred: Linezolid	No data
	Alternatives: Daptomycin Ceftaroline Linezolid	Alternatives: Insufficient clinical data for the treatment of AHO to recommend other oral antibiotics with in vitro activity against <i>S. aureus</i>	No data

*Uncomplicated AHO is defined as the presence of infection in a single site with rapid clinical response to antimicrobial therapy (i.e., resolution of fever and marked improvement in clinical signs within 3-5 days), with no more than a single early surgical procedure required as source control for the infection. Complicated infections may require a longer duration of treatment than uncomplicated infections, particularly if multiple surgeries are needed to establish source control.

[†]Not all antibiotics listed have been prospectively evaluated in clinical trials of acute bacterial osteomyelitis. Prospective studies to evaluate the effectiveness of a range of antibiotic doses in various degrees of severity of uncomplicated and complicated osteomyelitis, with or without surgery, have not been performed, although retrospective data have been reported for many antibiotics in the treatment of pediatric osteomyelitis.

[‡]The suggested duration of therapy should be based on clinical course (pace of resolution of fever and clinical signs and symptoms, noting the need for surgical intervention[s] required, if any), supported by decline of inflammatory markers.

[§]Preferred and alternative agents are selected based on published data regarding in vitro activity, clinical efficacy, and safety. Agents are generally listed in order of preference.

[#]Many of the β -lactamase-stable penicillins cause significant phlebitis in peripheral veins with infusion; administration through a central venous catheter is preferred.

[¶]Alternative antibiotics that may display in vitro activity against *S. aureus* have not been evaluated prospectively in AHO. However, linezolid has been evaluated in prospective controlled clinical trials for invasive methicillin-resistant *S. aureus* nosocomial pneumonia in adults and is more likely to provide adequate therapy of invasive *S. aureus* AHO, compared with trimethoprim-sulfamethoxazole, which is not recommended for children with AHO by the Infectious Diseases Society of America (IDSA) Clinical Practice Guidelines for Treatment of Methicillin-Resistant *Staphylococcus aureus* Infections in Adults and Children.

AHO, Acute hematogenous osteomyelitis.

From Woods CR, Bradley JS, Chatterjee A, et al. Clinical practice guideline by the Pediatric Infectious Diseases Society of America: 2021 guideline on diagnosis and management of acute hematogenous osteomyelitis in pediatrics. *J Pediatric Infect Dis Soc*. 2021;10(8):801-844. [Table 4](#).

the efficacy of treating osteomyelitis caused by *B. henselae* is uncertain, azithromycin plus rifampin may be considered.

When the pathogen is identified and antibiotic susceptibilities are determined, appropriate adjustments should be made to use the antibiotic with the narrowest spectrum, lowest adverse effect profile, and most favorable host tolerance. If a pathogen is not identified and a patient's condition is improving, therapy is continued with the initially selected antibiotic or an agent with a comparable spectrum of coverage. This selection is more complicated owing to the presence of MRSA isolates in the community. If a pathogen is not identified and a patient's condition is not improving, repeat aspiration or biopsy and the possibility of a noninfectious condition should be considered.

Duration of antibiotic therapy is individualized depending on the organism isolated and clinical course. Most acute cases of osteomyelitis, including those caused by *S. aureus*, can be treated with antibiotics for 21-28 days provided that the patient shows prompt resolution of signs and symptoms (within 5-7 days) and the CRP has normalized; a total of 4-6 weeks of therapy may be required for those with substantially slower resolution of symptoms or normalization of CRP. For group A streptococcus, *S. pneumoniae*, or

Haemophilus influenzae type b, treatment duration may be shorter. A total of 7-10 postoperative days of treatment is adequate for *Pseudomonas* osteochondritis from a foot puncture wound, when curettage of infected tissue has been performed. Immunocompromised patients generally require prolonged courses of therapy, as do patients with mycobacterial or fungal infection.

For typical cases, antimicrobial agents may be changed from intravenous to oral administration when a patient's condition clearly has improved, the child is afebrile, and bacteremia has resolved. Oral cephalexin (75-100 mg/kg/24 hr divided q8hr) may be used for susceptible staphylococcal or streptococcal infections. Oral clindamycin (30-40 mg/kg/24 hr divided q6-8hr) can be used to complete therapy for children with clindamycin-susceptible CA-MRSA or for patients who are seriously allergic or cannot tolerate β -lactam antibiotics. The oral regimen decreases the risk of complications related to prolonged intravenous therapy, is more comfortable for patients, and permits treatment outside the hospital if adherence to treatment can be ensured. Outpatient intravenous antibiotic therapy via a central venous catheter can be used for completing therapy at home for (1) patients unable or unwilling to take oral medication; (2) patients with underlying medical conditions that make enteral

drug absorption unreliable; (3) patients without comparable oral antibiotic options (e.g., resistant bacteria, drug allergy); and (4) patients with disseminated infection (e.g., endocarditis, pulmonary septic emboli). Catheter-related complications, including infection or mechanical problems, can lead to readmission or emergency department visits.

In children with venous thrombosis complicating osteomyelitis, administration of anticoagulants under the supervision of a hematologist until the thrombus has resolved is a generally accepted practice, although high-quality evidence to support this practice is lacking; antibacterial therapy alone may be sufficient.

Surgical Therapy

When frank pus is obtained from subperiosteal or metaphyseal aspiration or is suspected based on MRI findings, a surgical drainage procedure is usually indicated. Surgical intervention is also often indicated after a penetrating injury and when a retained foreign body is possible. In selected cases, catheter drainage performed by an interventional radiologist is adequate.

Treatment of chronic osteomyelitis consists of surgical removal of sinus tracts and sequestrum, if present. Surgical implantation of antibiotics is not generally recommended. Antimicrobial therapy, typically administered orally, is continued for several months or longer until clinical and radiographic findings suggest that healing has occurred. Normalization of CRP and ESR is expected in successful treatment of chronic osteomyelitis but does not by itself indicate clearance of the underlying infection. Many patients with chronic osteomyelitis have a normal CRP and ESR even at the onset of illness.

Physical Therapy

The major role of physical therapy is a preventive one. If a child is allowed to lie in bed with an extremity in flexion, limitation of extension can develop within a few days. The affected extremity should be kept in extension with sandbags, splints, or, if necessary, a temporary cast. Casts are also indicated when there is a potential for pathologic fracture. After 2-3 days, when pain is easing, passive range-of-motion exercises are started and continued until the child resumes normal activity. In neglected cases with flexion contractures, prolonged physical therapy is required.

Prognosis

When pus is drained and appropriate antibiotic therapy is given, the improvement in signs and symptoms is rapid. Failure to improve or worsening by 48-72 hours requires review of the appropriateness of the antibiotic therapy, the need for surgical intervention, or the accuracy of the diagnosis. Acute phase reactants may be useful as monitors. In acute osteomyelitis, the serum CRP typically decreases below 2 mg/dL within 7-10 days after starting treatment, whereas the ESR typically rises for 5-7 days and then falls slowly, dropping sharply after 10-14 days. Failure of CRP to follow the usual course should raise concerns about the adequacy of therapy. Recurrence of disease and development of chronic infection after treatment occur in <10% of patients.

Because children are in a dynamic state of growth, sequelae of skeletal infections might not become apparent for months or years; therefore long-term follow-up is necessary, with close attention to range of motion of joints and bone length. Although firm data about the impact of delayed treatment on outcome are not available, it appears that initiation of medical and surgical therapy within 1 week of onset of symptoms provides a better prognosis than delayed treatment.

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Chapter 726

Septic Arthritis

Samir S. Shah

Without early recognition and prompt institution of appropriate medical and surgical therapy, septic arthritis in infants and children has the potential to damage the synovium, adjacent cartilage, and bone and may cause permanent disability.

Etiology

Staphylococcus aureus (see Chapter 227.1) is the most common cause of bacterial arthritis in all age groups. Methicillin-resistant *S. aureus* (MRSA) accounts for a high proportion (>25%) of community *S. aureus* isolates in many areas of the United States and throughout the world. Group A streptococcus (see Chapter 229) and *Streptococcus pneumoniae* (pneumococcus; see Chapter 228) historically cause 10–20%; *S. pneumoniae* is most likely in the first 2 years of life, but its frequency has declined since the introduction of the pneumococcal conjugate vaccines. *Kingella kingae* is recognized as a relatively common etiology with improved culture and polymerase chain reaction (PCR) methods in children younger than 4 years (see Chapters 239 and 725). In sexually active adolescents, *gonococcus* (see Chapter 238) is a common cause of septic arthritis and tenosynovitis, usually of small joints or as a monoarticular infection of a large joint (knee). *Neisseria meningitidis* (see Chapter 237) can cause either a septic arthritis that occurs in the first few days of illness or a reactive arthritis that is typically seen several days after antibiotics have been initiated. Group B streptococcus (see Chapter 230) is an important cause of septic arthritis in neonates. Q fever and brucellosis should be considered in endemic areas and with an exposure risk.

Fungal infections usually occur as part of multisystem disseminated disease; *Candida* arthritis can complicate systemic infection in neonates with or without indwelling vascular catheters. Primary viral infections of joints are rare, but arthritis accompanies many viral (parvovirus, mumps, rubella live vaccines) syndromes, suggesting an immune-mediated pathogenesis.

A microbial etiology is confirmed in approximately 65% of cases of septic arthritis. In addition, some cases treated as bacterial arthritis are actually postinfectious (gastrointestinal or genitourinary) reactive arthritis (see Chapter 198) rather than primary infection. Lyme disease produces an arthritis more like a rheumatologic disorder and not typically suppurative.

Epidemiology

Septic arthritis is more common in young children. Half of all cases occur by 2 years of age, and 75% of all cases occur by 5 years of age. Adolescents and neonates are at risk of gonococcal septic arthritis.

Most infections in otherwise healthy children arise hematogenously. Less commonly, infection of joints can follow penetrating injuries or procedures such as trauma, arthroscopy, prosthetic joint surgery, intraarticular steroid injection, and orthopedic surgery. Immunocompromised patients and those with rheumatologic joint disease are also at increased risk of joint infection.

Pathogenesis

Septic arthritis primarily occurs as a result of hematogenous seeding of the synovial space. Less often, organisms enter the joint space by direct inoculation or extension from a contiguous focus. The synovial membrane has a rich vascular supply and lacks a basement membrane, providing an ideal environment for hematogenous seeding. The presence of bacterial products (endotoxin or other toxins) within the

joint space stimulates cytokine production (tumor necrosis factor- α , interleukin-1) within the joint, triggering an inflammatory cascade. The cytokines stimulate chemotaxis of neutrophils into the joint space, where proteolytic enzymes and elastases are released by neutrophils, damaging the cartilage. Proteolytic enzymes released from the synovial cells and chondrocytes also contribute to destruction of cartilage and synovium. Bacterial hyaluronidase breaks down the hyaluronic acid in the synovial fluid, making the fluid less viscous and diminishing its ability to lubricate and protect the joint cartilage. Damage to the cartilage can occur through increased friction, especially for weight-bearing joints. The increased pressure within the joint space from accumulation of purulent material can compromise the vascular supply and induce pressure necrosis of the cartilage. Synovial and cartilage destruction results from a combination of proteolytic enzymes and mechanical factors.

CLINICAL MANIFESTATIONS

Most septic arthritides are monoarticular. The signs and symptoms of septic arthritis depend on the age of the patient. Early signs and symptoms may be subtle, particularly in neonates. As with osteomyelitis, neonates might exhibit **pseudoparalysis** or pain that limits voluntary movement of the affected extremity (e.g., diaper changes). Septic arthritis in neonates and young infants is often associated with adjacent osteomyelitis caused by transphyseal spread of infection, although osteomyelitis contiguous with an infected joint can be seen at any age (see [Chapter 725](#)).

Older infants and children might have fever and pain, with localizing signs such as swelling, erythema, and warmth of the affected joint. With involvement of joints of the pelvis and lower extremities, limp or refusal to walk often occurs.

Erythema and edema of the skin and soft tissue overlying the site of infection are seen earlier in septic arthritis than in osteomyelitis because the bulging infected synovium is usually more superficial, whereas the metaphysis is located more deeply. Septic arthritis of the hip is an exception because of the deep location of the hip joint. With Lyme arthritis, joint swelling is typically quite prominent and may be disproportionate to the relatively lesser degree of pain and limited range of motion when compared with suppurative arthritis. Lyme arthritis has a predilection for large joints, particularly the knees and hips, and may be either monoarticular or pauciarticular at presentation.

Joints of the lower extremity constitute 75% of all cases of septic arthritis ([Table 726.1](#)). The elbow, wrist, and shoulder joints are involved in approximately 25% of cases, and small joints are uncommonly infected, except in gonococcal arthritis. Suppurative infections of the hip, shoulder, elbow, and ankle in infants and children may be associated with an adjacent osteomyelitis of the proximal femur, proximal humerus, proximal radius, and distal tibia because the metaphysis extends intraarticularly. Concomitant osteomyelitis is less common

in older children and adolescents as their anatomy and physiology become more adult-like.

DIAGNOSIS

The white blood cell count (WBC) and differential, ESR, and CRP are generally elevated in children with joint infections, but elevations are nonspecific and might not be helpful in distinguishing between infection and other inflammatory processes. Most children with septic arthritis will have normal leukocyte counts and ESR at presentation, and normal test results do not preclude the diagnosis of septic arthritis. A CBC, however, may assist with assessment of illness severity (e.g., anemia, thrombocytopenia) or with identification of other causes of the patient's symptoms (e.g., leukemia).

Blood cultures should be performed in all cases of suspected septic arthritis but are positive in ~20% of proven or probable septic arthritis. Cervical, anal, and throat cultures should be obtained when gonococcus is suspected. Aspiration of the joint fluid provides the optimal specimen to confirm the diagnosis. Most large joint spaces are easy to aspirate, but the hip can pose technical problems; ultrasound guidance facilitates aspiration. Although yield for joint aspirate cultures is higher than from blood cultures, the overall culture yield when combining both methods remains less than 50%. Multiplex bacterial PCR panels have a yield around 50% from joint fluid specimens, but this increase over culture is almost entirely because of their enhanced ability to detect *K. kingae*. Other strategies to increase detection of *K. kingae* include prompt inoculation onto solid media and inoculation of the joint fluid in blood culture bottles. A diagnosis of Lyme arthritis is made via a two-step test of an ELISA or IFA followed by a reflex Western blot for samples that are positive or equivocal by the first methodology. Patients with Lyme arthritis are seropositive because arthritis is a late manifestation of infection. PCR is rarely necessary but can detect *Borrelia burgdorferi* in joint aspirate specimens in cases of Lyme arthritis.

Synovial fluid analysis for cell count, differential, protein, and glucose has limited utility in diagnosing infectious arthritis. Joint fluid WBC counts >50,000 cells/mm³ (often >100,000 cells/mm³) suggest bacterial infection as the most likely etiology, but this finding is neither sensitive nor specific enough to exclude or confirm a bacterial infection in isolation. When the results of joint aspirate cell counts and culture are not strongly suggestive of a joint infection, but the clinical presentation is worrisome for a bacterial etiology, infectious causes of sympathetic joint effusions such as adjacent pyomyositis and osteomyelitis should be investigated by MRI (see [Chapter 725](#)).

Monitoring elevated CRP may be of value in assessing response to therapy or identifying complications. In addition, patients with adjacent infections complicating septic arthritis more frequently have a CRP >10–13 mg/dL compared with patients with septic arthritis alone. Other findings such as older age, prolonged symptoms, bacteremia, alterations in other lab values (such as elevated absolute neutrophil count or thrombocytopenia), and failure to rapidly improve with therapy have been less consistently associated with adjacent infection. Nonetheless, adjacent infection should be considered in patients demonstrating multiple risk factors.

Radiographic Evaluation

Radiographic studies play a crucial role in evaluating septic arthritis. Conventional radiographs and ultrasonography are performed as part of the routine workup. CT, MRI, and radionuclide studies can all contribute to establishing the diagnosis in selected cases ([Fig. 726.1](#)).

Plain Radiographs

Plain films can suggest the diagnosis of septic arthritis by showing widening of the joint capsule, soft tissue edema, and obliteration of normal fat lines. Plain films can also help to exclude other causes of joint pain such as fractures. Plain films of the hip can show medial displacement of the obturator muscle into the pelvis (the obturator sign), lateral displacement or obliteration of the gluteal fat lines, and elevation of Shenton's line with a widened arc.

Table 726.1 Distribution of Hematogenous Bacterial Arthritis*

BONE	PERCENT (%)
Knee	~35
Hip	~25
Ankle	~10
Elbow	~10
Wrist	~4
Shoulder	~5
Small joints	~1–2

*Excludes Lyme disease and immune-complex postinfectious arthritis. Viral (rubella, mumps, chikungunya) infectious arthritis is often small and multiple joints. Septic bursitis (shoulder, prepatellar) may be confused with bacterial joint infections.

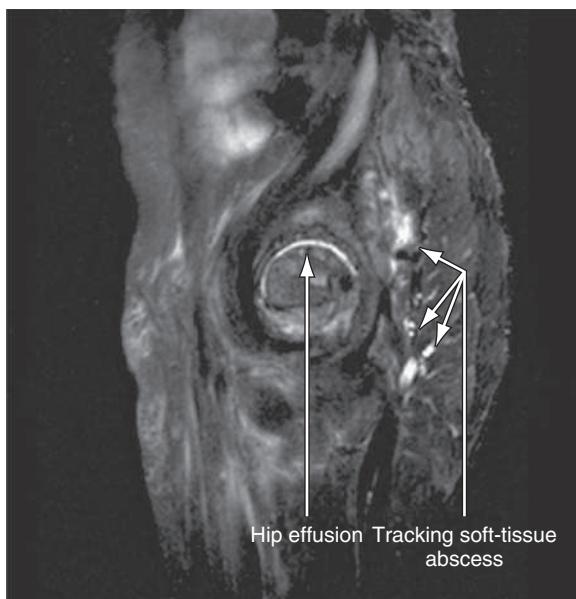


Fig. 726.1 MRI of staphylococcal septic arthritis of left hip, with fluid collections between planes of gluteal muscles. Arrows indicate fluid collection. (From Matthews CJ, Weston VC, Jones A, et al. *Bacterial septic arthritis in adults*. Lancet. 2010;375:846–854.)

Ultrasonography

Ultrasonography is included with plain films in routine evaluations because it is particularly helpful in detecting joint effusion and fluid collection in the soft tissue and subperiosteal regions. Ultrasonography is highly sensitive in detecting joint effusion, particularly for the hip joint, where plain radiographs are normal in more than 50% of cases of septic arthritis of the hip. Ultrasonography can serve as an aid in performing hip aspiration.

Magnetic Resonance Imaging and Computed Tomography

MRI and CT can confirm the presence of joint fluid in patients with suspected osteoarthritis infections but are not routinely indicated. MRI is useful in evaluating for adjacent osteomyelitis or pyomyositis but is typically reserved for cases when the index of suspicion for these conditions is high. Considerations include patient factors such as younger age, the clinical presentation (e.g., protracted pain preceding joint swelling), the results of laboratory investigations such as joint aspiration and CRP, and response to therapy.

DIFFERENTIAL DIAGNOSIS

The differential diagnosis of septic arthritis depends on the joint or joints involved and the age of the patient. For the hip, transient synovitis, pyomyositis, Legg-Calvé-Perthes disease, slipped capital femoral epiphysis, psoas abscess, and proximal femoral, pelvic, or vertebral osteomyelitis, as well as diskitis, should be considered. Transient synovitis (toxic synovitis) is a postinfectious arthritis of the hip that is often seen in young children after a viral infection (see Chapter 719.2). For the knee, distal femoral or proximal tibial osteomyelitis, pauciarticular rheumatoid arthritis, and referred pain from the hip should be considered. Knee or thigh pain may be referred from the hip. Other conditions such as trauma, cellulitis, pyomyositis, sickle cell disease, hemophilia, Lyme arthritis, leukemia, serum sickness, and IgA vasculitis (Henoch-Schönlein purpura) can mimic purulent arthritis. When several joints are involved, serum sickness, collagen vascular disease, rheumatic fever, and IgA vasculitis should be considered. Arthritis is one of the extraintestinal manifestations of inflammatory bowel disease. Reactive arthritis after a variety of bacterial (gastrointestinal or

genital) and parasitic infections, streptococcal pharyngitis, or viral hepatitis can resemble acute septic arthritis (see Chapter 198).

TREATMENT

Optimal treatment of septic arthritis requires coordination between primary care physicians, orthopedic surgeons, and radiologists.

Surgical Therapy

Drainage and irrigation of the infected joint via arthroscopy or arthrotomy is typically performed to decompress the joint and remove inflammatory debris. The decision to proceed to one of these procedures after arthrocentesis is based on the gross appearance of the joint fluid, or joint fluid WBC and differential, in the context of the clinical presentation and the specific joint that is infected. Infection of the hip is generally considered a surgical emergency because of the vulnerability of the blood supply to the head of the femur. For joints other than the hip, daily aspirations of synovial fluid may be required. In general, one or two subsequent aspirations suffice. If fluid continues to accumulate after 4–5 days, arthrotomy or video-assisted arthroscopy is needed. At the time of surgery, the joint is flushed with sterile saline solution. Antibiotics are not instilled because they are irritating to synovial tissue, and adequate amounts of antibiotic are achieved in joint fluid with systemic administration.

Antimicrobial Therapy

Empiric antimicrobial therapy should be started immediately in a child with presumed septic arthritis who is ill-appearing or has a rapidly progressive infection. Antibiotic therapy may be deferred until initial joint aspirate has been collected for diagnostic purposes in a child with presumed septic arthritis who does not appear clinically ill.

The initial empirical antimicrobial therapy is based on likely bacterial pathogens at various ages, the results of the Gram stain of aspirated material, and additional considerations. In neonates, an antistaphylococcal penicillin, such as nafcillin or oxacillin (100–200 mg/kg/24 hr divided q6hr IV), and a broad-spectrum cephalosporin, such as cefepime (100–150 mg/kg/24 hr divided q12hr IV), provide coverage for the *S. aureus*, group B streptococcus, and gram-negative bacilli. If MRSA is a concern, clindamycin or vancomycin is selected instead of nafcillin or oxacillin. If the neonate is a small premature infant or has a central vascular catheter, the possibility of nosocomial bacteria (*S. aureus*, gram-negative enterics, or *Pseudomonas aeruginosa*) or fungi (*Candida*) should be considered.

In children with septic arthritis, empirical therapy to cover for *S. aureus* and streptococci includes at minimum nafcillin (100–200 mg/kg/24 hr divided q6hr). In preschool-age children (i.e., 6 months to 4 years), empiric therapy should include an antibiotic with activity against *Kingella kingae* as well as *S. aureus*, such as cefazolin (100–150 mg/kg/24 hr divided q8hr).

In areas where methicillin resistance is noted in ≥10–15% of community-acquired methicillin-resistant *S. aureus* (CA-MRSA) strains, adding an antimicrobial that is effective against local CA-MRSA isolates is suggested. Vancomycin (15 mg/kg q6hr IV) is preferred in patients who are ill-appearing, suspected to be bacteremic, or if local clindamycin resistance is more than 10–15%. Clindamycin (30–40 mg/kg/24 hr divided q6–8hr) is a good alternative when treating CA-MRSA infections. For immunocompromised patients, combination therapy is usually initiated, such as with vancomycin and ceftazidime, cefepime, or piperacillin/tazobactam, with or without an aminoglycoside. Adjunct therapy with dexamethasone has been shown in some studies to decrease the duration of fever and promote a more rapid decline in inflammatory markers, but this is not yet part of routine care. **Lyme arthritis** is treated with oral doxycycline (4.4 mg/kg/24 hr divided q12hr) for 28 days in children >8 years old. For children <8 years old, oral amoxicillin (50 mg/kg/24 hr divided q8hr) or cefuroxime (30 mg/kg/24 hr divided q12hr) is recommended. A second 28-day course may be considered for patients with persistent or recurrent symptoms after completing the initial course of treatment. Intravenous ceftriaxone (50 mg/kg q24hr IV) for 14–28 days may be considered as an initial or second course of therapy for severe or refractory cases.

Empirical antimicrobials are narrowed to targeted therapy when the pathogen is identified. If a pathogen is not identified and a patient's condition is improving, therapy is continued with the antibiotic selected

initially. If a pathogen is not identified and a patient's condition is not improving, consideration should be given to the need for repeat aspiration, the presence of an extraarticular infection requiring surgical debridement, or the possibility of a noninfectious etiology. In such cases, MRI may be performed to assist with subsequent management decisions.

Duration of antibiotic therapy is individualized depending on the organism isolated and the clinical course. A total of 10–14 days is usually adequate for streptococci, *S. pneumoniae*, and *K. kingae*; longer therapy may be needed for *S. aureus* and gram-negative infections (3 weeks), concomitant osteomyelitis (4 weeks), extensive disease, or slow response to treatment. Normalization of CRP in addition to a normal examination supports discontinuing antibiotic therapy. The prognostic significance of an improved but still minimally elevated ESR in the third or fourth week of therapy is not clear if all other clinical and laboratory parameters are favorable. In selected patients, obtaining a plain radiograph of the joint before completing therapy can provide evidence (typically periosteal new bone) of a previously unappreciated contiguous site of osteomyelitis that would likely prolong antibiotic treatment. Oral antibiotics can be used to complete therapy once the patient is afebrile for 48–72 hours and is clearly improving.

Surgically administered intraarticular antibiotics are not recommended.

PROGNOSIS

Improvement in signs and symptoms occurs rapidly after joint drainage and antibiotic administration. Failure to improve or worsening by 48–72 hours requires review of the appropriateness of the antibiotic therapy, the need for surgical intervention, and the correctness of the diagnosis. CRP may be useful to monitor response to therapy. Failure of CRP to decline should raise concerns about the adequacy of therapy. Recurrence of disease and development of chronic infection after treatment occur in <10% of patients.

Septic arthritis can lead to numerous long-term sequelae in children, including leg-length discrepancy or angular deformity from growth arrest, limitations in range of motion due to chondral damage, and avascular necrosis of the femoral head from septic arthritis of the hip. The overall rate of these sequelae with current therapies is <5%. However, children are in a dynamic state of growth, so these abnormalities might not become apparent for months or years; therefore long-term follow-up is necessary, with close attention to range of motion of joints and bone length. Involvement of the hip is associated with a higher rate of sequelae. Initiation of medical and surgical therapy within 1 week of onset of symptoms provides a better prognosis than delayed treatment.

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Section 2

Sports Medicine

Chapter 727

Prevention of Injuries

Gregory L. Landry and Andrew M. Watson

The Centers for Disease Control and Prevention, the American College of Sports Medicine, and the American Academy of Pediatrics all recommend daily moderate to vigorous physical activity for all adolescents. Physical activity has favorable effects on blood pressure, body composition, and serum lipid levels in youths and is associated with lower rates of cardiovascular disease, type 2 diabetes mellitus, osteoporosis, and colon and breast cancer among adults.

Pediatricians should promote physical activity to their patients, especially those with lower rates of physical activity and sports participation, including children with special healthcare needs (see Chapter 756) and those from lower socioeconomic groups. Physicians also have the responsibility of providing medical clearance for participation in physical activity and sports as well as for the diagnosis and rehabilitation of injuries.

Approximately 30 million children and adolescents participate in organized sports in the United States. Around 3 million sport-related injuries occur annually in young athletes, if injury is defined as time lost from the sport. Deaths in sports are rare, with the majority of nontraumatic deaths caused by cardiac diseases (see Chapter 485). Nonetheless, approximately 30% of life-threatening injuries in children presenting to an emergency room are sports related. Overall, injury rates and injury severity in sports increase with age and pubertal development, related to the greater speed, strength, and intensity of competition.

Identifying mechanisms of injury and establishing and enforcing rules that reduce the likelihood of that mechanism of injury, including penalizing dangerous play, have reduced catastrophic injury rates. Injury rates also have been reduced by removing environmental hazards, such as trampolines in gymnastics and stationary (versus breakaway) bases in softball, and by modifying heat injury rates in soccer tournaments by adding water breaks and reducing the playing time. Certain types of equipment can mitigate the risk of some injuries, such as the use of mouth guards to reduce dental injuries. The most consistently identified risk factor for injury is prior injury. In other words, although reinjury may often be due to insufficient recovery and rehabilitation of a prior injury, appropriate rehabilitation reduces injury risk. Preseason training for adolescent athletes, with an emphasis on speed, agility, core strength, landing mechanics, and flexibility, is associated with lower injury rates in soccer and fewer serious knee injuries in female athletes. Traditional stretching maneuvers or massage have not been demonstrated to reduce the risk of injury or muscle soreness, but ankle taping and use of lace-up ankle braces are helpful in preventing ankle injuries. One setting for implementing some of these prevention strategies and for detecting unrehabilitated injuries and medical problems that could affect participation in sports is the preparticipation sports examination (PSE).

PREPARTICIPATION SPORTS EXAMINATION

The PSE is performed with a directed history and physical examination, including a screening musculoskeletal examination (see Table 485.2 in Chapter 485). It identifies possible problems in 1–8% of athletes and excludes fewer than 1% from participation. The PSE is not a substitute for the recommended comprehensive annual evaluation, which looks at behaviors that are potentially harmful to teens, such as sexual activity, drug use, and violence, and assesses for depression and suicidal ideation and addresses broader issues of prevention. Table 727.1 identifies the purposes of the PSE. If possible, the PSE should be combined with the comprehensive annual health visit with an emphasis on preventive healthcare (see Chapters 13 and 28).

State requirements for how often a young athlete needs a PSE differ, ranging from annually to entry to a new school level (middle school, high school, college). At a minimum, a focused, annual interim evaluation should be done on an otherwise healthy young athlete. The PSE is optimally performed 3–6 weeks before the start of practice.

History and Physical Examination

The essential components of the PSE are the history and focused medical and musculoskeletal screening examinations. Identified problems require more investigation (Table 727.2). While many medical conditions should not limit sports participation, many specialty organizations have released recommendations regarding sports participation (Table 727.3). In the absence of symptoms, no screening laboratory tests are required. Return to sports after COVID-19 infection is based on the severity of infection (mild, moderate, or ICU admission and/or MIS-C), and the intensity of follow-up, especially for those with active cardiac involvement during the acute phase of the illness (Fig. 727.1).

Seventy-five percent of significant findings are identified by the history; a standardized questionnaire given to the parent and athlete is important

Table 727.1 Objectives of the Preparticipation Sports Examination

- Determination of the general health of the athlete
- Disclosure of defects that may limit participation
- Detection of conditions that may predispose the athlete to injury
- Determination of optimal level of performance
- Classification of the athlete according to individual qualifications
- Fulfillment of legal and insurance requirements for organized athletic programs
- Evaluation of size and level of maturation of younger athletes
- Improvement of fitness and performance
- Provision of opportunities for students to compete who have either physiologic or pathologic health conditions that may preclude blanket approval
- Provision of the opportunity to counsel youths and answer health and personal questions
- Entry of the athlete into the local sports medicine system, establishing a doctor-patient relationship that continues

From Sanders B, Blackburn TA, Boucher B. Preparticipation screening—the sports physical therapy perspective. *Int J Sports Phys Ther.* 2013;8(2):180–193. **Table 1.**

Table 727.2 Preparticipation Sports Examination

COMPONENT OF THE PHYSICAL EXAMINATION	CONDITION TO BE DETECTED
Vital signs	Hypertension, cardiac disease, bradycardia or tachycardia
Height and weight	Obesity, eating disorders, malabsorption
Vision and pupil size	Legal blindness, absent eye, anisocoria, amblyopia
Lymph node	Infectious diseases, malignancy
Cardiac (performed standing and supine)	Heart murmur, prior surgery, dysrhythmia, femoral pulses
Pulmonary	Recurrent and exercise-induced bronchospasm, chronic lung disease
Abdomen	Organomegaly, abdominal mass
Skin	Contagious diseases (impetigo, herpes, staphylococcal, streptococcal)
Genitourinary	Varicocele, undescended testes, tumor, hernia
Musculoskeletal	Acute and chronic injuries, physical anomalies (scoliosis)

because the young athlete might not know or might forget important aspects of the history. The questionnaire should include questions about the family history and the patient's previous medical, surgical, cardiac, pulmonary, neurologic, dermatologic, visual, psychologic, musculoskeletal, and endocrinologic problems, as well as about prior heat illness, medications, allergies, immunizations, and diet. The most commonly identified problems are *unrehabilitated injuries*. An investigation of previous injuries, including diagnostic tests, treatment, and present functional status, is indicated.

Sudden death during sports can result from undetected cardiac disease, such as hypertrophic or other **cardiomyopathies** (see Chapter 488), **anomalous coronary vessels** (see Chapter 481.2), or a ruptured aorta in **Marfan syndrome** (see Chapter 743). In many cases, the underlying heart disease is not suspected, and death is the first sign of underlying heart disease (see Chapter 485). However, in approximately 25–50% of cases, preceding symptoms of dizziness, chest pain, syncope, palpitations, shortness of breath, and/or a family history of early, unexpected death are identified retrospectively. Chest radiographs, electrocardiograms, and

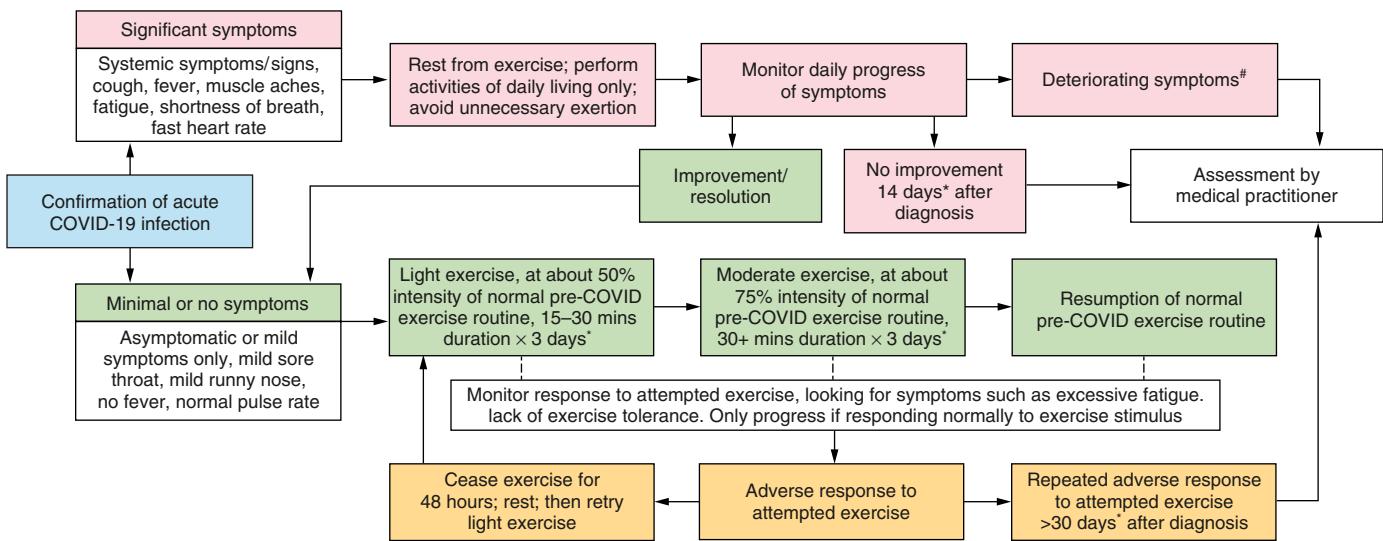
Table 727.3 Sports Participation Recommendations by Condition

CONDITION	RECOMMENDATION
Hemophilia	Restrict contact or collision sports until evaluation by a hematologist who can assess degree of hemostatic abnormality and the sport-specific risk
Sickle cell disease	Individual decision-making given variation in phenotypic expression
Diabetes mellitus	No restrictions
Skin infections (herpes gladiatorium, tinea gladiatorium, impetigo, molluscum contagiosum, warts, and MRSA)	Prevent transmission by: <ul style="list-style-type: none"> • Covering infected site • Using prophylactic medications as prescribed • No sharing of personal items • Thorough cleaning of equipment
Mononucleosis infection	Light, noncontact activity may be introduced as tolerated 3 weeks after illness onset with avoidance of contact/collision sports until 4 weeks after illness onset
Blood-borne infections (hepatitis B, hepatitis C, HIV)	No restrictions
COVID-19 infection	See Fig. 727.1
Heat illness, history of	Gradual acclimatization to heat over 7–14 days, avoid participation while ill (fever, skin rash, viral symptoms), ensure free access to fluids at all times, consume sodium-containing food/fluids to replace insensible losses, rest periods of at least 3 hours before practice or games
Down syndrome	Individual decision-making based on the presence of congenital heart disease or atlantoaxial instability

Data from Herman D, Gadi N, Peck E. Team medical coverage. In Miller MD, Thompson SR, eds. *DeLee, Drez, & Miller's Sports Medicine*, 5th ed. Philadelphia: Elsevier, 2020.

echocardiograms are not recommended as routine screening tests in the United States, but screening electrocardiograms are recommended in a number of other countries and are becoming more commonly used among higher risk groups in the United States, such as collegiate and professional athletes. If there is a suspicion of heart disease, such as a history of syncope, presyncope, palpitations, or excessive dyspnea with exercise, or a family history of a condition such as hypertrophic cardiomyopathy or prolonged QT or Marfan syndrome, the evaluation should be complete and include a 12-lead electrocardiogram, an echocardiogram, Holter or event-capture monitoring, and a stress test with electrocardiographic monitoring. Recommendations for participation with identified cardiac disease should be made in consultation with a cardiologist.

Sports may also be classified by intensity (Fig. 727.2) and contact (Table 727.4). Athletes may seek to participate in sports against medical advice and have done so successfully for professional sports. Section 504(a) of the Rehabilitation Act of 1973 prohibits discrimination against disabled athletes if they have the capabilities or skills required to play a competitive sport. This was reinforced through the Americans with Disabilities Act of



- Dry, post-viral cough may persist beyond the acute COVID-19 infection
- Individuals should be 10 days post diagnosis or onset of symptoms (or have negative RAT on days 6 & 7), before rejoining group / team activities
- *Number of days at each step may be modified in high performance sport, where athletes have the benefit of close medical supervision
- Those with medical comorbidities should adopt a more cautious approach to return to exercise
- # **Cardiac symptoms should be treated as a medical emergency: Pressure, tightness, squeezing pain in chest, arms, neck, jaw, or back, cold sweat, difficulty breathing, collapse, sudden dizziness**

Fig. 727.1 Graduated return to exercise after COVID-19 infection. RAT, rapid home antigen test. (From Hughes DC, Orchard JW, Partridge EM, et al. Return to exercise post-COVID-19 infection: a pragmatic approach in mid-2022. *J Sci Med Sport*. 2022;25:544–547. Fig. 1.)

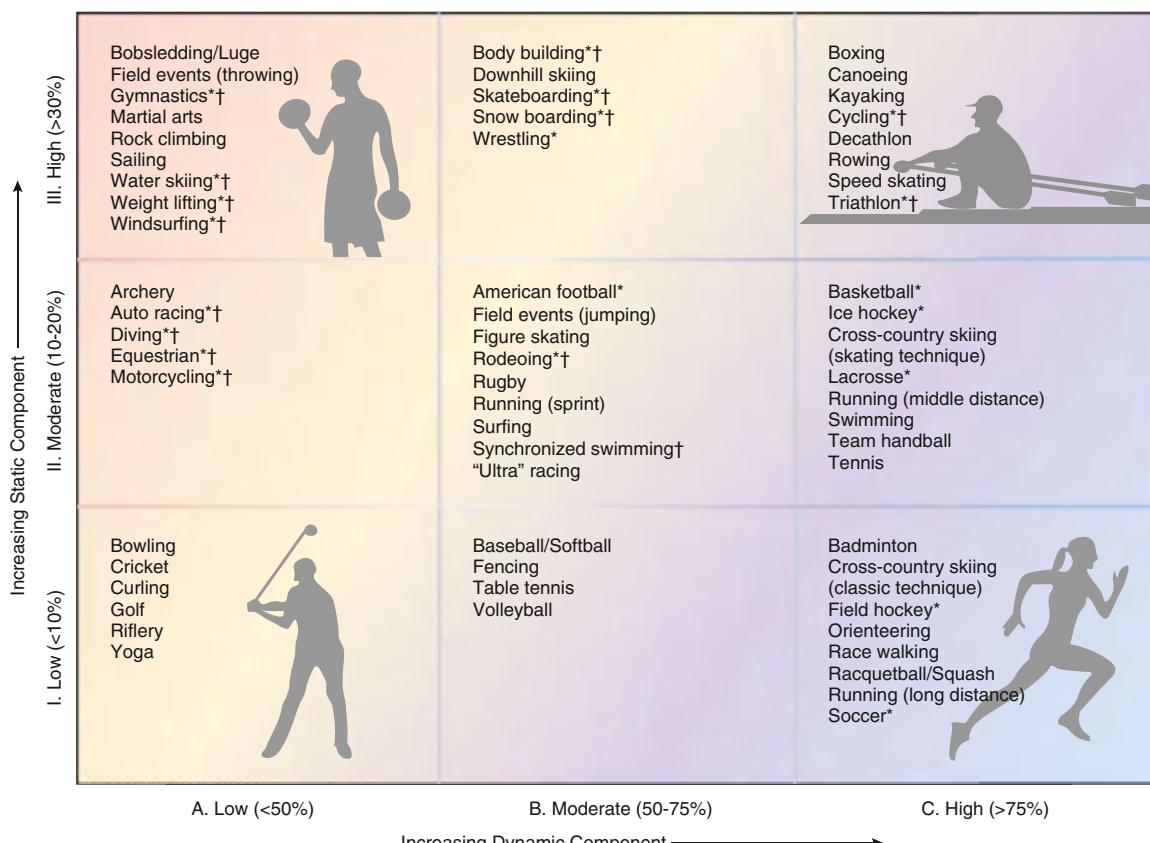


Fig. 727.2 Classification of sports. This classification is based on peak static and dynamic components achieved during competition; however, higher values may be reached during training. The increasing dynamic component is defined in terms of the estimated percentage of maximal oxygen uptake ($\dot{V}O_{2\max}$) achieved and results in an increasing cardiac output. The increasing static component is related to the estimated percentage of maximal voluntary contraction reached and results in an increasing blood pressure load. The lowest total cardiovascular demands (cardiac output and blood pressure) are shown in the palest color, with increasing dynamic load depicted by increasing blue intensity and increasing static load by increasing red intensity. Note the graded transition between categories, which should be individualized on the basis of player position and style of play. *Danger of bodily collision (see Table 727.4 for more detail on collision risk). †Increased risk if syncope occurs. (Modified from Mitchell JH, Haskell W, Snell P, et al. 36th Bethesda conference. Task force 8: classification of sports. *J Am Coll Cardiol*. 2005;45:1364–1367.)

Table 727.4

Sports According to Risk of Impact and Educational Background

	JUNIOR HIGH SCHOOL	HIGH SCHOOL/COLLEGE
Impact expected	American football Ice hockey Lacrosse Wrestling Karate/judo Fencing Boxing	American football Soccer Ice hockey Lacrosse Basketball Wrestling Karate/judo Downhill skiing Squash Fencing Boxing
Impact may occur	Soccer Basketball Field hockey Downhill skiing Equestrian Squash Cycling	Field hockey Equestrian Cycling Baseball/softball Gymnastics Figure skating
Impact not expected	Baseball/softball Cricket Golf Riflery Gymnastics Volleyball Swimming Track and field Tennis Figure skating Cross-country skiing Rowing Sailing Archery Weightlifting Badminton	Cricket Golf Riflery Volleyball Swimming Track and field Tennis Cross-country skiing Rowing Sailing Archery Weightlifting Badminton

From Levine BD, Baggish AL, Kovacs RJ, et al. Eligibility and disqualification recommendations for competitive athletes with cardiovascular abnormalities: Task force 1: classification of sports: dynamic, static, and impact: a scientific statement from the American Heart Association and American College of Cardiology. *J Am Coll Cardiol.* 2015;66(21):2350–2355.

1990. Participation in competitive sports is considered a privilege, not a right. *Knapp v Northwestern University* established that “difficult medical decisions involving complex medical problems can be made by responsible physicians exercising prudent judgment (which will be necessarily conservative when definitive scientific evidence is lacking or conflicting) and relying on the recommendations of specialist consultants or guidelines established by a panel of experts.”

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sprains are graded I–III. A *grade I* sprain is defined as mild damage to a ligament or ligaments without instability of the affected joint. A *grade II* sprain is considered a partial tear to the ligament, such that it exhibits excessive laxity but has a firm endpoint on examination. A *grade III* sprain is a complete tear of the ligament with instability to the affected joint and without a firm endpoint on examination. A **strain** is an injury to a muscle or tendon, and these are also graded I–III. *Grade I* muscle strains involve disruption of only a few muscle fibers, pain is mild to moderate, and range of motion and strength are at or near normal. *Grade II* strains represent a more significant, partial tear of the muscle and frequently involve loss of range of motion and strength. *Grade III* strains are defined as complete rupture of the musculotendinous unit. On examination, *grade III* strains, and often *grade II* strains, present with ecchymosis and a palpable step-off at the site of injury. A **contusion** is a crush injury to any soft tissue. The history of the injury is especially helpful in assessing musculoskeletal trauma. More severe injuries, including fractures or internal derangement of a joint, may have acute signs and symptoms such as immediate swelling, deformity, numbness or “give-way” weakness, a loud painful pop, mechanical locking of the joint, or instability.

Overuse Injuries

Overuse injuries are caused by repetitive microtrauma that exceeds the body’s rate of repair. This can occur in muscles, tendons, bone, bursae, cartilage, and nerves. Overuse injuries can occur in all sports but are more commonly seen in sports emphasizing repetitive motion such as swimming, running, tennis, baseball pitching, and gymnastics. Factors leading to overuse injuries can be categorized as extrinsic (i.e., training errors, poor equipment, or workout surface) and intrinsic (i.e., athlete’s anatomy or medical conditions). Training error is the most commonly identified factor. For example, at the beginning of the training program, athletes might violate the “10% rule” by increasing the duration or intensity of workouts by more than 10% per week. This may exceed the body’s capacity to recover between bouts of activity, leading to accumulated microtrauma that manifests as an overuse injury. Intrinsic factors include abnormal biomechanics that may be due to underlying anatomic causes (e.g., leg-length discrepancy, pes planus, pes cavus, tarsal coalition, valgus heel, external tibial torsion, and femoral anteversion), muscle imbalance, inflexibility, and medical conditions (deconditioning, nutritional deficits, amenorrhea, and obesity). To identify the cause of an overuse injury, the athlete should be questioned about the specifics of their training. Specifically, runners, for example, should be asked about their shoes, orthotics, running surface, weekly mileage or time spent running per week, speed or hill workouts, and previous injuries and rehabilitation. When causative factors are identified, they can be modified or eliminated so that after rehabilitation the athlete does not suffer a recurrent overuse injury.

For athletes engaged in excessive training that causes an overuse injury, curtailing all exercise may not be necessary. Treatment incorporates a reduction of training load (relative rest) combined with a rehabilitation program designed to return athletes to their sport as soon as possible while minimizing risk of re-injury. Early identification of an overuse injury requires less alteration of the workout regimen. In addition, proper sleep, nutrition, and stress management can optimize recovery between bouts of activity, promoting physiologic adaptation and reducing the risk of accumulated damage that leads to injury.

It has become more commonplace for young athletes to *specialize* in a single sport and engage in year-round training. Families should be advised about the risks of specialization in young athletes because this is associated with burnout, decreased motivation and enjoyment, and increased risk of overuse injuries. This is especially evident among baseball pitchers, in whom repeated exposure to the highly repetitive and forceful throwing motion can damage the tissues in the elbow and shoulder in a growing athlete. These athletes and their parents should be counseled to diversify their sport participation at younger ages, which may increase their enjoyment and performance in sport, as well as reduce the risk of overuse injury.

The goals of treatment in overuse injuries are to control pain and spasm to rehabilitate flexibility, strength, endurance, and proprioceptive deficits (Table 728.1). In many overuse injuries, the role of inflammation in the process is minimal. For most injuries to tendons, the term

Chapter 728

Management of Musculoskeletal Injury

Gregory L. Landry and Andrew M. Watson

MECHANISM OF INJURY

Acute Injuries

Sprains, strains, and contusions account for the majority of musculoskeletal injuries. A **sprain** is an injury to a ligament or joint capsule. Most

Table 728.1 Staging of Overuse Injuries

GRADE	GRADING SYMPTOMS	TREATMENT
I	Pain only after activity Does not interfere with performance or intensity Generalized tenderness Disappears before next session	Modification of activity, consider cross-training, home rehabilitation program
II	Minimal pain with activity Does not interfere with performance More localized tenderness Disappears before next session	Modification of activity, cross-training, home rehabilitation program
III	Pain interferes with activity and performance Definite area of tenderness Usually disappears between sessions	Significant modification of activity, strongly encourage cross-training, home rehabilitation program, and outpatient physical therapy
IV	Pain with activities of daily living Pain does not disappear between sessions Marked interference with performance and training intensity	Discontinue activity temporarily, cross-training only, oral analgesic, home rehabilitation program, and intensive outpatient physical therapy
V	Pain interferes with activities of daily living Signs of tissue injury (e.g., edema) Chronic or recurrent symptoms	Prolonged discontinuation of activity, cross-training only, oral analgesic, home rehabilitation program, and intensive outpatient physical therapy

tendinitis is no longer used because there is little or no inflammation on histopathology of the affected tendons. Rather, there is evidence of microscopic trauma to the tissue and a disorientation of the tendon fibers. Most of these entities are more appropriately called **tendinosis**; when the tendon tissue is scarred and when markedly abnormal, **tendinopathy**. With tendinosis, there is less of a role for antiinflammatory medication in the treatment, except as an analgesic.

Novel treatments are emerging for the effective treatment of chronic tendinopathies. Under ultrasound guidance, pathologic areas of tendon tissue can be targeted with injections of autologous blood or platelet-rich plasma to stimulate a proinflammatory and more robust healing response. Platelet-rich plasma is a controversial therapy with a mixed body of evidence related to its effectiveness for certain acute and chronic tendinopathies; there is a lack of consensus regarding its role in the standard of care. Pathologic tissue can also be targeted with percutaneous needle fenestration or tenotomy, and tendon-fat pad adhesions can also be addressed through mechanical needle scraping or hydrodissection techniques using ultrasound.

INITIAL EVALUATION OF THE INJURED EXTREMITY

Initially, the examiner should determine the quality of the peripheral pulses and capillary refill rate, as well as the gross motor and sensory function to assess for neurovascular injury. The first priorities are to maintain vascular integrity and skeletal stability.

Criteria for immediate attention and rapid orthopedic consultation include vascular compromise, nerve compromise, and open fracture. With the latter, the exposed wound should be covered with sterile saline-soaked gauze, the injured limb should be padded and splinted, and systemic antibiotics should be administered. Pressure should be applied to any site of excessive bleeding. Additional criteria include deep laceration over a joint, unreducible dislocation, grade III (complete) tear of a muscle-tendon unit, and displaced, significantly angulated fractures.

TRANSITION FROM IMMEDIATE MANAGEMENT TO RETURN TO PLAY

Rehabilitation of a musculoskeletal injury should be initiated on the day of the injury.

Phase 1

Limit further injury, control swelling and pain, and minimize strength and flexibility losses. PRICE principles (Protection, Rest, Ice, Compression, and Elevation) need to be applied. Crutches, air stirrups for ankle sprains, slings for arm injuries, and elastic wraps (4–8 inches) for compression are a helpful inventory of medical supplies. Ice can be

placed directly over the injury as tolerated for 20 minutes continuously 3 or 4 times per day until the swelling resolves. Compression limits further bleeding and swelling but should not be so tight that it limits perfusion. Elevation of the extremity promotes venous return and limits swelling. A nonsteroidal antiinflammatory drug (NSAID) or acetaminophen are indicated for analgesia.

Pain-free isometric strengthening and range of motion exercises should be initiated as soon as tolerable. Pain inhibits full muscle contraction; deconditioning results if the pain and resultant disuse persist for days to weeks, thus delaying recovery. Education about the nature of the injury and the specifics of rehabilitation exercises, including handouts with written instructions and drawings demonstrating the exercises, are helpful.

Phase 2

Improve strength and range of motion (e.g., flexibility) while allowing the injured structures to heal. Protective devices are removed when the patient's strength and flexibility improve and activities of daily living are pain-free. Flexibility can then be addressed by a program of specific stretches, held for 15–30 seconds for three to five repetitions, once or twice daily. A physical therapist or athletic trainer is invaluable in guiding the athlete through this process. Protective devices might need to be used upon return to sports participation. Swimming, water jogging, and stationary cycling are good, low-impact aerobic exercises that can allow the injured lower extremity to be used pain-free while maintaining cardiovascular fitness.

Phase 3

Achieve near-normal strength and flexibility of the injured structures and further improve or maintain cardiovascular fitness. Strength and endurance are improved under controlled conditions using elastic bands and closed kinetic chain exercises (movement of multiple joints and limb segments with foot fixed to a static surface, such as the floor or wall) at this point and then progressing next to using exercise equipment followed by free weights. Additional sensory proprioceptive training allows the athlete to redevelop the kinesthetic sense critical to joint function and stability during activity.

Phase 4

Return to exercise or competition without restriction. When the athlete has reached normal range of motion, strength, proprioception, and endurance, the athlete can initiate sports-specific exercises. The athlete will transition from the rehabilitation program to functional rehabilitation appropriate for the sport. Substituting sports participation for rehabilitation is inappropriate; rather, there should be progressive stepwise

functional return to a full activity or play program. For instance, a basketball player recovering from an ankle injury might begin a walk-run-sprint-cut program before returning to competition. At any point in this progression, if pain is experienced, the athlete needs to stop, apply ice, avoid running for 1-2 days, continue to perform ankle stabilizing exercises, and then resume running at a lower intensity and progress accordingly.

Relative Rest and Return-to-Play Guidelines

Relative rest refers to the concept that the athlete participates in rehabilitation and return to sport activities provided the injured structures do not hurt during or within 24 hours of the activity. Exercising beyond the pain threshold delays recovery.

IMAGING

Traditional imaging modalities such as x-ray, ultrasound, MRI, and CT are well-established in the routine diagnostic workup of musculoskeletal injury. An obvious advantage of ultrasound is a lack of radiation. It is also better tolerated by younger children who may have difficulty complying with MRI or CT protocols. Dynamic movement or stressing of a limb, joint, or structure can provide valuable diagnostic information and can easily be compared to the contralateral side for comparison. Snapping or popping sensations, suspected intramuscular hematomas, stress fractures, and prognostic scrutiny of strains, sprains, and tendinopathies are all high-yield applications of diagnostic musculoskeletal sonography. Ultrasound imaging can also increase the accuracy of therapeutic injections, improving injection efficacy while simultaneously reducing adverse outcomes by erroneous needle placement.

DIFFERENTIAL DIAGNOSES OF MUSCULOSKELETAL PAIN

Traumatic, rheumatologic, infectious, hematologic, psychologic, congenital, and oncologic processes—especially under the age of 12 years old—can result in a presenting complaint of musculoskeletal pain. Symptoms such as fatigue, weight loss, rash, multiple joint complaints, fever, chronic or recent illness, pain out of proportion to the nature of the injury, and persistent pain despite conservative care suggest a diagnosis other than sports-related trauma. The possibility of child abuse, including sexual abuse, should not be overlooked. Incongruity between the patient's history and physical examination findings should lead to further evaluation. A negative review of systems with an injury history consistent with the physical findings suggests a sports-related etiology.

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728.1 Growth Plate Injuries

Gregory L. Landry and Andrew M. Watson

Approximately 20% of pediatric sports injuries seen in the emergency department are fractures, and 25% of those fractures involve an epiphyseal growth plate or physis (see Chapter 724). Growth in long bones occurs in three areas and is susceptible to injury. Immature bone can be acutely injured at the physis (e.g., Salter-Harris fractures, see Chapter 724.2), the articular surface (e.g., osteochondritis dissecans [OCD]), or the apophysis (e.g., avulsion fractures). Males suffer nearly twice as many physis fractures as females, with the highest incidence of fracture occurring during peak height velocity (females: age 12 ± 2.5 years; males: age 14 ± 2 years). The physis is a pressure growth plate and is responsible for longitudinal growth in bone. The apophysis is a bony outgrowth at the attachment of a tendon and is a traction physis. The epiphysis is the end of a long bone, distal or proximal to the long bone, and contains articular cartilage at the joint.

Physeal injuries of the upper extremity are most commonly seen at the distal radius in the growing child or adolescent and are typically due to excessive force applied to the upper extremity. Injuries of this nature can be seen in athletes, including those participating in gymnastics, cheerleading, ice skating, hockey, and weightlifting. Mechanisms of

injury include falls onto an outstretched hand or repetitive dorsiflexion and axial loading through the distal radius (see Chapter 734). Chronic wrist pain can be seen in up to 79% of young gymnasts—particularly female gymnasts between the ages of 12-14 years—and is commonly termed **gymnasts' wrist** (see Chapter 722). With repetitive axial loading, temporary metaphyseal ischemia may be induced, preventing cartilage calcification and causing the physis to widen. With widening of the distal radial physis, microfractures can develop. Clinical features include radial wrist pain (particularly dorsal) that is aggravated with passive and active hyperextension activities and relieved with suspension of the offending activity. Tenderness or focal pain around the circumference of the distal radius is often noted. Differential diagnosis includes metacarpal fractures, scaphoid fracture and, in the older child or adolescent, de Quervain tenosynovitis. Juvenile idiopathic arthritis, malignancy, and infection need to be considered in a child with a painful, swollen wrist without a history of trauma. X-rays of the wrist can be helpful, particularly when compared to the contralateral extremity. Radiographs can show physeal widening with cystic changes involving the metaphyseal segment, breaking of the distal epiphysis, and, in later stages, positive ulnar variance (longer ulna compared to the radius). MRI is often helpful for stress fractures when radiographs are inconclusive and will show signs of stress reaction (bone marrow edema, periosteal reaction, etc.), even if a fracture line is not evident. PRICE principles are followed with nonnarcotic pain management. Salter-Harris fractures types I and II can be treated with closed reduction and immobilization. Ulnar-shortening osteotomy may be necessary in the athlete with significant ulnar positive variance. Physeal injuries at the knee (distal femur, proximal tibia) are rare, whereas those at the ankle (distal fibula most commonly) are more frequent—typically occurring as a result of an inversion injury—and predominantly consist of Salter-Harris I fractures.

Growth disturbance following a growth plate injury is a function of location of the physeal fracture. This influences the probability that a physeal bar will form, resulting in growth arrest. In the upper extremity, the areas making the largest contribution to longitudinal growth are the proximal humerus and distal radius and ulna; in the lower extremities, the distal femur and the proximal tibia and fibula are the greatest contributors to longitudinal growth. Injuries to these areas are more likely to cause growth disturbance compared with physeal injuries at the other end of these long bones. The type of physis fracture relative to the risk of growth disturbance is described by the Salter-Harris classification system (see Table 724.1). A grade I injury is least likely to result in growth disturbance, and grade V is the most likely fracture to result in growth disturbance.

Osteochondritis dissecans (OCD) affects the subchondral bone and overlying articular surface (see Chapter 718.3). With avascular necrosis of subchondral bone, the articular surface can flatten, soften, or break off in fragments. The etiology may be related to repetitive stress injury in some patients. OCD most commonly presents in the lower extremities at the knee, affecting the lateral aspect of the medial femoral condyle in 70% of patients, the lateral femoral condyle in 20%, and the patella in 10%. In the upper extremities, it is most frequently seen at the elbow (Fig. 728.1)—affecting the capitellum—and is often associated with repetitive overhead throwing or swinging activities (e.g., baseball). Other sites where OCD lesions are seen are the ankle (talus) and radial head. OCD classically affects athletes in their second decade. The most common presentation is poorly localized, vague joint pain. There is rarely a history of recent acute trauma. Some OCD lesions are asymptomatic and incidental—diagnosed on “routine” radiographs—whereas others manifest as joint effusion, pain, decreased range of motion, and mechanical symptoms (e.g., locking, popping, or catching). Activity usually worsens the pain.

Physical examination might show no specific findings. Sometimes tenderness over the involved condyle can be elicited by deep palpation. Diagnosis is usually made with plain radiographs. Treatment of OCD includes both nonoperative and surgical management (Chapter 718.3). Long-term sequelae can be seen in up to 25% with atypical lesions, older age, effusion, and lesions of large size.



Fig. 728.1 Osteochondritis dissecans in the elbow. (Copyright Laurel Sauer, 2017.)



Fig. 728.2 Anterior inferior iliac spine avulsion. (Copyright Laurel Sauer, 2017.)

Avulsion fractures occur when a forceful muscle contraction dislodges the apophysis from the bone. They occur most commonly around the hip (Fig. 728.2) and are typically treated nonsurgically if no significant displacement of the avulsed fragment is present. Acute fractures to other apophyses (i.e., knee and elbow) require urgent orthopedic consultation. Chronically increased traction at the muscle-apophysis attachment can lead to repetitive microtrauma and pain at the apophysis. The most common areas affected are the knee (**Osgood-Schlatter and Sinding-Larsen-Johansson disease**), the ankle (**Sever disease**) (Fig. 728.3), the proximal fifth metatarsal (**Iselin disease**), and the medial epicondyle (**Little Leaguer's elbow**). Traction apophysitis of the knee and ankle can often be treated in a primary care setting. The main goal of treatment is to minimize the intensity and incidence of pain and disability. Exercises that increase the strength, flexibility, and endurance of the muscles attached at the apophysis, using the relative rest principle, are appropriate. The use of a patellar strap can provide benefit in reducing the traction force placed upon the tibial apophysis during activity. Symptoms can last for 12–24 months if untreated. As growth slows, symptoms abate.

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728.2 Shoulder Injuries

Gregory L. Landry and Andrew M. Watson

Shoulder pain associated with radiating symptoms down the arm should raise the possibility of a neck injury (see Chapter 730). Neck pain and tenderness or limitation of cervical range of motion requires cervical spine immobilization and transfer of the athlete for further evaluation. If there is no neck pain, tenderness, or limitation of motion of the cervical spine, the shoulder is likely the site of the primary injury.



Fig. 728.3 Calcaneal apophysitis (Sever disease). (Copyright Laurel Sauer, 2017.)

CLAVICLE FRACTURES

Clavicle fracture is one of the most common shoulder injuries (see Chapter 724.3). Injury is usually sustained by a fall on the lateral side of an adducted shoulder, on an outstretched hand, or by direct blow. Approximately 80% of fractures occur in the middle third of the clavicle. With younger children, plastic bowing of the clavicle may be present instead of an overt fracture but should be treated in the same fashion. Treatment is conservative and includes the use of an arm sling or figure-of-8 brace for comfort and protection. An arm sling is preferred because it is generally more comfortable and easier to apply with similar clinical outcomes. Healing time is shorter in comparison to that in adults—generally 3–6 weeks. An additional 2- to 3-week period of protection from contact/collision activities is recommended after clinical and radiographic healing is achieved to prevent re-injury. If nondisplaced, most medial and lateral clavicular fractures can be managed similar to middle-third clavicular fractures. Displaced lateral and medial third fractures require orthopedic consultation because of a higher incidence of acromioclavicular (AC) osteoarthritis (lateral), and physeal involvement (medial). **Distal clavicular osteolysis** is likely an overuse injury associated with slow dissolution and resorption of

bone. The cause of injury is unclear, appearing most consistent with a stress reaction or fracture at the site of considerable force. This lesion is commonly seen in weightlifting athletes and can be seen in older children. Nonoperative treatment, including activity limitations, ice, NSAIDs, and cortisone injections, can be helpful. For weightlifters, narrowing their hand spacing on the barbell and slowing descent phase of the bench press to end 4–6 cm above the chest are recommended activity modifications. For those not willing to modify weightlifting activity or those with persistent symptoms despite conservative care, surgery can be very successful and involves removal of the distal clavicle (approximately 1 cm) with no loss of strength and full return to activity anticipated.

ACROMIOCLAVICULAR JOINT SEPARATION

An AC joint separation most commonly occurs when an athlete sustains a direct blow to the acromion with the humerus in an adducted position, forcing the acromion inferiorly and medially. Force is directed toward the AC joint and coracoclavicular ligaments because of the inherent stability of the sternoclavicular joint. Patients have point tenderness at the AC joint, pain with lifting their arms above the level of their shoulder, and possibly an apparent step-off between the distal clavicle and the acromion (Fig. 728.4).

Type I AC joint injuries involve isolated sprain of the AC ligament with the periosteal sleeve intact (Fig. 728.5). There is no visible deformity, and the radiographs are normal. Pain is elicited with adduction of the humerus across the chest and palpation of the AC joint. **Type II** injuries involve disruption of the AC and coracoclavicular ligaments, as well as partial disruption of the periosteal sleeve. Radiographs may show slight widening of the AC joint, though the distance between the clavicle and the coracoid process is unchanged in comparison to the uninjured shoulder. Treatment of type I and type II AC injuries is conservative and consists of ice, NSAIDs, and a sling for immobilization. Shoulder range of motion exercises and strengthening of the rotator cuff, deltoid, and trapezius musculature

are incorporated early in the rehabilitative course once pain-free range of motion is achieved in order to prevent residual joint stiffness. A short course of physical therapy may be helpful if range of motion limitations are present 2–4 weeks out from injury. Consideration for return to play is made when the patient no longer has focal AC joint tenderness, exhibits full, painless range of motion, has strength sufficient to be functionally protected from a collision or fall, and can perform maneuvers required within their sport. Typically, return to play from a type I AC injury is 1–2 weeks, and 2–4 weeks for type II.

Type III AC joint injury is more severe, involving further tearing of the AC and coracoclavicular ligaments and disruption of the periosteal sleeve with instability of the distal clavicle because of deltotrapezial fascial detachment. Radiographs will commonly show superior displacement of the distal clavicle from the coracoid of 25–100%. The treatment of type III AC injuries is controversial. Many can be treated nonoperatively—similar to that described for types I and II AC injuries—if there is no damage to the overlying skin or neurovascular compromise to the injured limb. The patient should be counseled that this injury is likely to result in a noticeable defect to ascertain whether this is acceptable. Surgery for type III AC injuries is uncommon and primarily for athletes involved with throwing sports or for cosmesis. **Types IV, V, and VI** AC joint injuries have progressive worsening of ligamentous and fascial disruption with varied locations of the clavicular displacement. These injuries should be referred to an orthopedist for consultation and operative repair.

ANTERIOR GLENOHUMERAL DISLOCATION

The most common mechanism of injury causing an anterior glenohumeral dislocation is contact with the shoulder abducted to 90 degrees and forcefully externally rotated. Patients complain of severe pain and that their shoulder “popped out of place” or “shifted.” Patients with an unreduced anterior dislocation have a hollow region inferior to the acromion and a bulge in the anterior portion of the shoulder caused by anterior displacement of the humeral head. Abnormal sensation of the lateral deltoid region and the extensor surface of the proximal forearm should be assessed to evaluate for concomitant injury to the radial or musculocutaneous nerves, respectively.

Reduction of a dislocated shoulder should be made expediently, assuming that there is no crepitus to suggest a fracture. Numerous safe methods for closed reduction have been described, including the traction–counter traction technique, the **Stimson maneuver**, and the abduction maneuver. Postreduction radiographs are helpful and may show evidence of a posterior lateral humeral head impaction fracture (**Hill-Sachs lesion**). Injuries to the surrounding soft tissues, including the anterior capsule and labrum, are best evaluated by MRI—often with an accompanying arthrogram of the glenohumeral joint. Once reduced, initial treatment of a dislocation includes placing the patient into an arm sling for comfort and protection. The duration of immobilization is controversial and may last from a few days to 6 weeks. The most significant risk after an acute traumatic dislocation is recurrence. Most sports medicine practitioners encourage early range of motion and strengthening exercises as tolerated. Rehabilitation focuses on progressive strengthening of the rotator cuff, deltoid, and periscapular muscles at increasing degrees of abduction and external rotation. Strengthening of the rotator cuff muscles is extremely important because they are the dynamic stabilizers of the glenohumeral joint and are integral to the prevention of future dislocation. Plyometric exercises also may be incorporated near the end of rehabilitation to improve proprioceptive function in preparation for return to athletics. Patients can return to play when strength, range of motion, and proprioception are equal to the uninjured shoulder to the extent that they are able to protect the shoulder and perform sports-specific activities without pain. Surgery is to be considered in cases of recurrent dislocations or in those individuals that fail to heal adequately after prolonged rehabilitation. Additionally, early operative repair should be considered for athletes participating in contact or collision sports that inherently have higher recurrence rates.



Fig. 728.4 Palpitation of acromioclavicular joint. (From Anderson SJ. Sports injuries. *Curr Probl Pediatr Adolesc Health*. 2005;35:105–176.)

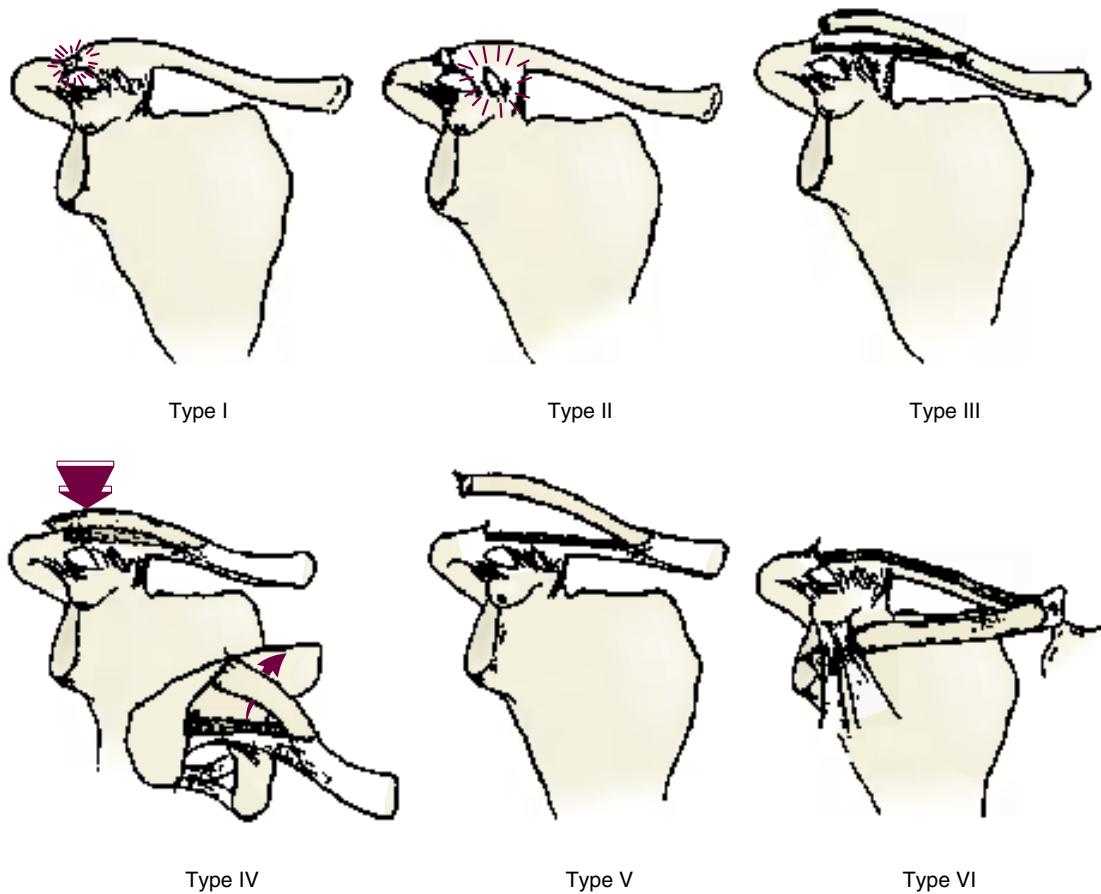


Fig 728.5 Rockwood's classification of acromioclavicular (AC) joint injuries in children. Type I, sprain of the AC ligaments without disruption of the periosteal tube. Type II, partial disruption of the periosteal tube. This may produce some AC instability. Type III, large split in the periosteal tube allowing superior displacement of the lateral clavicle. Type IV, large split in the periosteal tube (large arrow) with posterior displacement of the lateral clavicle through the trapezius muscle (curved arrow). Type V, complete disruption of the periosteal tube with displacement of the clavicle through the deltoid and trapezius muscles into the subcutaneous tissues. Type VI, inferior dislocation of the distal clavicle below the coracoid process. (Redrawn from Sanders JO, Rockwood CA, Curtis RJ. Fractures and dislocations of the humeral shaft and shoulder. In Rockwood CA, Wilkins KE, Beaty JH, eds. Fractures in Children. Vol 3. Philadelphia, PA: Lippincott-Raven; 1996:974.)

ROTATOR CUFF INJURY

The muscles of the rotator cuff consist of the supraspinatus, infraspinatus, teres minor, and subscapularis. The function of these muscles is to rotate the humerus and stabilize the humeral head against the glenoid. The supraspinatus is most commonly injured, either by an acute traumatic injury or chronic tendinosis from overuse. Specifically, rotator cuff tendinosis commonly presents with the complaint of pain with overhead arc of motion, such as with throwing, lifting, or reaching for objects above one's head. Pain is often poorly localized about the shoulder, although it may be referred to the deltoid. The onset of pain is often insidious and is commonly associated with increased frequency or duration of overhead throwing or lifting activities. Pain is exacerbated with overhead activities but is often present at rest as well; nighttime pain occurs in more severe cases. On exam, manual muscle testing of the rotator cuff muscles often produces pain and in some cases weakness in comparison to the uninjured shoulder. Supraspinatus tendinosis produces pain with active abduction against resistance in which the patient abducts the arm to 90 degrees, forward flexes to 30 degrees anterior to the parasagittal plane, and internally rotates the humerus.

The treatment of rotator cuff tendinosis includes relative rest from athletics or activities causing pain as well as the use of ice, analgesia, and/or NSAIDs. Strengthening of the rotator cuff and scapular stabilizer musculature, modifications of technique, and core strengthening are important components of rehabilitation often supervised by a physical therapist. In the young athlete, rotator cuff pain is most commonly

a result of glenohumeral instability and not rotator cuff impingement syndrome. The latter is more commonly seen in adults and is caused by impingement of the rotator cuff by the bony structures superior to it. As a result, treatment focusing on stretching alone can make symptoms worse. Return to play often includes gradual increases in load placed upon the rotator cuff as the patient resumes prior activities, such as an interval throwing program in baseball.

Glenoid labrum tears may present in similar insidious fashion to rotator cuff tendinosis or may be associated with an acute traumatic dislocation. This frequently manifests with pain in the glenohumeral joint and may be associated with mechanical sensations of clicking or catching in the shoulder. This can frequently be reproduced on exam. One of the most common lesions is a superior labrum anterior and posterior (SLAP) lesion. Throwing athletes are at particular risk. The mechanism of injury is thought to be related to a traction injury along the long head of the biceps at its attachment at the superior glenoid labrum, occurring during the throwing cycle. Radiographs are usually normal. MRI with arthrogram is the best study to identify glenoid labrum pathology (Fig. 728.6).

Proximal humeral stress fracture (epiphysiolysis) is an uncommon cause of proximal shoulder pain and is suspected when shoulder pain does not respond to routine measures. Gradual onset of deep shoulder pain occurs in a young athlete involved in repetitive overhead motion, such as in baseball, tennis, or swimming, but with no history of trauma. Tenderness is noted over the proximal humerus; the diagnosis is confirmed by detecting a widened epiphyseal plate on plain



Fig. 728.6 Coronal intermediate-weighted MRI showing superior labral tear (arrow) and tendinosis of the supraspinatus tendon (arrowhead). There is no adjacent perilabral edema, suggesting chronic injury. (From Chang, I-Yuan J, Polster JM. Pathomechanics and magnetic resonance imaging of the thrower's shoulder. Radiol Clin N Am. 2016;54(5):801-805. Fig. 13.)

radiographs, increased uptake on nuclear scan, or edema of the physis on MRI. Treatment is total rest from throwing for at least 6-8 weeks.

Non-sports-related conditions that need to be considered in any child with a painful shoulder include an undiagnosed Sprengel deformity. This deformity involves the scapula, which fails to descend from its cervical region overlying the first through fifth ribs. Children often present with a shortened neckline and a lack of normal scapular thoracic motion. Malpositioning of a glenoid can cause limited forward flexion and abduction of the shoulder. An omovertebral bar is present in up to 50% of cases. This bar connects the superior medial angle of the scapula and the cervical spine and consists of fibrous cartilaginous tissue or bone. Other regional abnormalities can include scoliosis with a prominent scapula on the convex side, congenital rib anomalies, and undiagnosed Klippel-Feil syndrome. Winging of the scapula raises the question of facioscapulohumeral muscular dystrophy. Family histories can be most helpful. Primary bone tumors (see Chapter 550) common to the upper extremities include Ewing sarcoma of the scapula and osteogenic sarcoma of the proximal humerus, in addition to osteoblastomas and chondroblastomas common to the diaphysis and epiphysis of long bones. The most common presenting manifestations of osteosarcoma are pain, upper limb dysfunction, and swelling. Similar presentations can be seen in Ewing sarcoma, along with weight loss and fever. Symptoms not responding to conservative treatment require further investigation and specialty consultation.

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728.3 Elbow Injuries

Gregory L. Landry and Andrew M. Watson

ACUTE INJURIES

The most commonly dislocated joint in childhood is the elbow. Radial head subluxation, or “nursemaid’s elbow,” comprises the majority of these (see Chapter 722). Posterior dislocation is the next most common type of **elbow dislocation**, typically resulting from falling backward onto an outstretched arm with the elbow in extension. The dislocation may be complete or incomplete—termed “perched”—with the trochlea subluxed upon the top of the coronoid process. The ulnar collateral



Fig. 728.7 Deflection of the supracondylar fat pad with a joint effusion (fat pad sign) (arrows) showing evidence of a fracture. (Copyright Laurel Sauer, 2017.)

ligament (UCL) is commonly disrupted along with other components of the soft tissue capsule about the elbow. Fractures of the olecranon (>80% occurrence) or medial epicondyle may be present as well. An obvious deformity is visualized with the olecranon process displaced prominently behind the distal humerus. Careful examination of the distal radius and ulnar pulses to assess vascular integrity of the distal upper arm is important because of the potential for injury to the brachial artery. Sensation to the distal extremity should also be assessed because of possible injury to the radial, median, and ulnar nerves. Reduction should be performed as soon as possible before significant swelling and muscle spasm potentially complicate the procedure. Longitudinal traction is applied to the forearm with gentle upward pressure on the distal humerus so that the coronoid process clears the trochlea. If reduction is unable to be performed, the arm should be placed in a padded splint and sling and the patient transported to an emergency facility.

Supracondylar humeral fractures can result from the same mechanism of injury as elbow dislocations and can be difficult to distinguish on exam from a posterior dislocation because of significant swelling about the elbow joint. These, too, can be complicated by concomitant injury to the brachial artery and to a lesser extent the median, radial, and ulnar nerves. The injury typically occurs in the first decade of life, which is associated with peak hyperlaxity of the elbow joint in children between the ages of 5-8 years. An acute compartment syndrome can develop after these fractures, which is associated with a fat pad sign on radiographs (Fig. 728.7). These fractures should be referred for orthopedic consultation and are discussed in more depth in Chapter 724.

Direct trauma to the elbow can cause bleeding and inflammation in the olecranon bursa resulting in **olecranon bursitis**. Aspiration is rarely required, and this injury can be managed with ice, compressive dressing, and analgesia (PRICE principles). An overlying elbow pad provides comfort during activity and prevents re-injury.

Chronic Injuries

Overuse injuries in the upper extremities occur primarily in throwing sports, sports that require repetitive wrist flexion or extension, or sports that demand weight-bearing on hands (gymnastics).

Little Leaguer’s elbow is a broad term for several different elbow problems. Throwing overhand creates valgus stress to the elbow with medial opening of the joint and lateral compressive forces. **Medial elbow pain** is a common complaint of young throwers, resulting from repetitive valgus overload of the wrist flexor-pronator muscle groups and their attachment on the medial apophysis. In preadolescents who still have maturing secondary ossification centers, traction apophysitis of the medial epicondyle is likely. Patients have tenderness along the medial epicondyle; pain is exacerbated by valgus stress or resisted wrist flexion and pronation. Wrist pain may be present in more severe cases. Radiographs may show widening of the growth plate at the medial

apophysis in comparison to the uninjured elbow. Treatment includes no throwing for 4-6 weeks and pain-free strengthening and stretching of the flexor-pronator group followed by a 1-2 week progressive functional throwing program with careful rehabilitation. Incorporation of core strengthening and scapular stabilizing exercises, as well as addressing proper throwing mechanics (to reduce the load upon the medial elbow), are important components of the rehabilitation program. Little Leaguer's elbow has to be treated with a period of rest from throwing because of the risk of nonunion of the apophysis and chronic pain. If pain occurs acutely, an avulsion fracture of the medial epicondyle must be considered. Radiographs should be taken in any thrower with acute elbow pain. If the medial epicondyle is avulsed (Fig. 728.8), orthopedic consultation is indicated.

In older adolescents and young adults with a fused apophysis, the structure at the elbow vulnerable to injury is the UCL. UCL sprains/tears are common in sports requiring high-velocity throwing or overhead activities. Medial elbow pain that is worst during the acceleration



Fig. 728.8 The many faces of little Leaguer's elbow in a 14-yr-old pitcher. A, AP radiograph and coronal oblique fat-saturated T2-weighted MRI demonstrate features of chronic medial epicondyle stress injury (yellow arrow) as well as findings of capitellar osteochondritis dissecans (white arrowhead). Proximal medial ulnar collateral ligament edema/grade 1 sprain also noted at the humeral attachment (red arrow). B, Sagittal short tau inversion recovery and fat-saturated T1-weighted MR arthrogram images emphasize the classic features of injury to the "metaphyseal equivalent" bone deep to the disorganized and obliterated secondary physis of the ossifying capitellum. (From Braithwaite KA, Marshall KW. The skeletally immature and newly mature throwing athlete. *Radiol Clin N Am*. 2016;54[5]:841-855. Fig. 11.)

phase of throwing is common. A loss of throwing velocity and control, as well as a sensation of elbow joint "opening" during throwing is also frequently described. On exam, focal tenderness to palpation over the UCL is present. Additionally, laxity may be appreciated with valgus stress of the elbow when flexed to 30 and/or 90 degrees. Radiographs are generally unremarkable. Diagnostic ultrasonography or MRI with arthrography is often necessary to assess the integrity of the UCL. Partial tears can be treated with a period of time off from throwing (2-4 weeks) followed by careful progressive rehabilitation as discussed earlier for medial elbow pain. If there is a complete tear, surgical repair is indicated if the athlete desires to continue a pitching career.

Medial epicondylitis, or golfer's elbow, is another common cause of medial elbow pain in the individual with fused apophyses. It is commonly caused by overuse of the flexor pronator muscle groups at their origin at the medial humeral epicondyle. This occurs frequently in athletics or activities with repetitive wrist flexion. Tenderness is noted over the medial epicondyle and exacerbated by passive wrist extension or resisted wrist flexion. Treatment includes rest from the inciting activity, ice, stretching and strengthening of the wrist flexors, forearm straps, counterforce bracing, and analgesia. Local injection of corticosteroids can be considered as an adjunctive treatment if initial conservative measures fail. Ulnar nerve dysfunction can be a complication of valgus overload and can occur with any of the diagnoses previously discussed. Persisting paresthesia or motor weakness in the ulnar nerve distribution should be evaluated with electromyography and nerve conduction studies. Diagnostic ultrasonography can also be of use to assess for focal thickening of the nerve, as a sign of irritation, as well as dynamically visualizing the nerve through the arc of elbow flexion to assess for subluxation over the medial epicondyle (Fig. 728.9).

Lateral elbow pain can be caused by compression during the throwing motion at the radiocapitellar joint. **Panner disease** is osteochondrosis of the capitellum that occurs between ages 7 and 12 years (Fig. 728.10). **OCD** of the capitellum occurs at age 13-16 years (see Fig. 728.1). Although patients with both conditions present with insidious onset of lateral elbow pain exacerbated by throwing, patients with OCD have mechanical symptoms (popping, locking) and, more commonly, decreased range of motion. Patients with Panner disease have no mechanical symptoms and often have normal range of motion. The prognosis of Panner disease is excellent, and treatment consists of relative rest (no throwing), brief immobilization, and repeat radiographs in 6-12 weeks to assess bone remodeling. In OCD, radiographs show a more focal lesion in the capitellum with eventual flattening and potentially fragmentation. MRI can be very helpful in early diagnosis and with subsequent staging. A diagnosis of OCD requires orthopedic consultation, with treatment depending on the severity of the lesion and fragmentation.

Lateral epicondylitis, or "tennis elbow," is the most common overuse elbow injury in adults but is relatively uncommon in children and adolescents (Fig. 728.11). It is a tendinosis of the extensor muscle origin at the lateral humeral epicondyle, which is commonly found in individuals performing activities requiring repetitive or prolonged grip. Tenderness is localized over the upper lateral epicondyle and is worsened with passive wrist flexion or resisted wrist extension. Treatment includes relative rest, analgesia, and specific stretching and strengthening exercises for the elbow and forearm. As with medial epicondylitis, corticosteroid injection can be considered as an adjunctive treatment if initial conservative measures fail. Improper equipment (i.e., wrong grip size or overstrung racket) and poor technique can contribute to the onset of symptoms. Return to play should be gradual and progressive to prevent re-injury.

Elbow injuries can be minimized but not necessarily prevented by preseason stretching and strengthening exercises. The importance of core strengthening and scapular stabilization with respect to preventing elbow and shoulder injuries in the throwing athlete cannot be overstated. The most important consideration for preventing elbow injuries in throwers is limitation of the number of pitches and advising players, coaches, and athletes that they should stop immediately when they experience elbow pain. If it persists, they need medical evaluation. It has been recommended that a young pitcher have age-specific limits

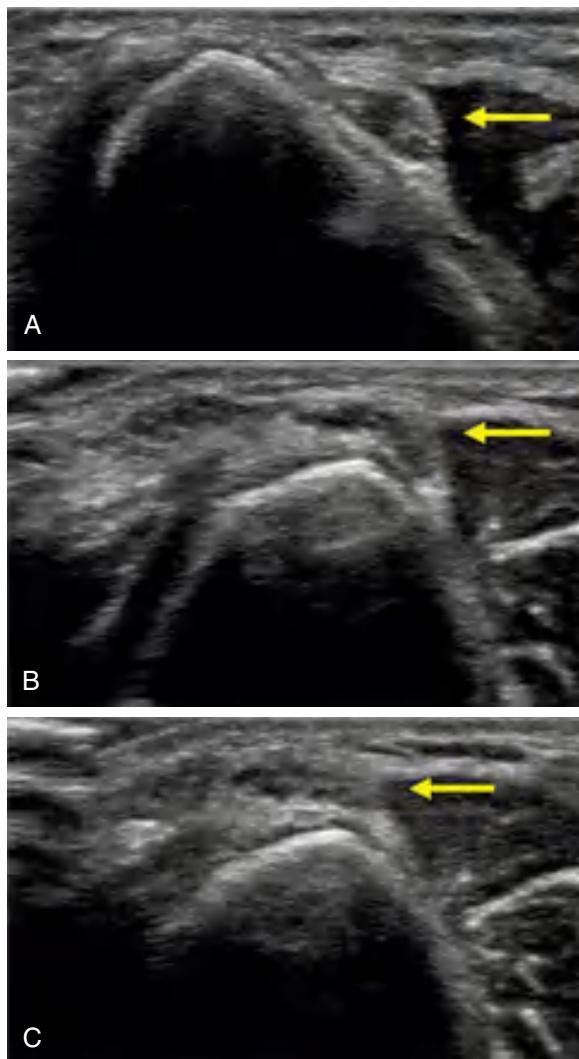


Fig. 728.9 Ulnar nerve subluxation. Dynamic ultrasound imaging of the ulnar nerve (arrow) in the ulnar groove at the elbow. A, The ulnar nerve positioned appropriately in the ulnar groove with the elbow extended. With elbow flexion, (B) the nerve becomes perched upon the medial epicondyle. As the elbow moves into terminal flexion, (C) the nerve is completely dislocated anteriorly over the medial epicondyle. (Courtesy Nicholas Goyeneche, MD, ultrasound clinic files, Ochsner Clinic Medical Center.)

on pitch counts, including the number of pitches thrown per game and per week, as well as maintaining appropriate days off between games pitched. A good rule of thumb is that the maximal number of pitches per game should be approximately 6 times the pitcher's age in years.

Other less-common problems that cause elbow pain are ulnar neuropathy/subluxation, tricipital or bicipital tendonitis (distal), olecranon apophysitis, and loose bodies. Non-sports-related injuries that need to be considered in the child with a painful elbow include undiagnosed congenital conditions such as radial dysplasia, including radial ulnar synostosis and mild persistent brachial plexus palsy. The elbow is not an uncommon site for inflammatory arthropitides, including juvenile idiopathic arthritis, sepsis, hemophilia, and sickle cell disease. Neoplasia to consider includes osteoblastomas and chondroblastomas, which are common in the diaphysis and epiphysis of longer bones, in addition to osteosarcoma. As always, in the child with persistent symptoms who is not responding to conservative care, further diagnostic workup is indicated.



Fig. 728.10 Panner disease. Note fragmentation of the humeral capitellum and flattening of the articular surface (arrow). (Copyright Laurel Sauer, 2017.)

728.4 Low Back Injuries

Gregory L. Landry and Andrew M. Watson

SPONDYLOLYSIS, SPONDYLOLISTHESIS, AND FACET SYNDROME

Spondylolysis

Spondylolysis, a common cause of back pain in athletes, is a stress fracture of the pars interarticularis (see Chapter 720.6). It can occur at any vertebral level but is most likely at L5. Complete spondylolysis has never been found in the newborn. Its occurrence increases between the ages of 5.5 and 6.5 years to a rate of 5%. Prevalence in adolescent athletes evaluated for low back pain is 13–47%. Besides hyperextension that causes an acute fracture, the mechanism of injury is either a congenital defect or hypoplastic pars. This is exacerbated by repetitive lumbar extension loading. Ballet, weightlifting, gymnastics, and football are examples of sports in which repetitive extension loading of the lumbar spine frequently occurs.

Patients often present with pain of insidious onset. However, there may be a precipitating injury, such as a fall, or a single episode of hyperextension. The pain is worse with extension, may radiate to the buttocks, and can eventually affect activities of daily living. Rest or supine positioning usually alleviates the pain.

On examination, the pain is reproduced with lumbar extension while standing, especially when standing on one leg (single-leg hyperextension test). Limited forward spinal flexion and tight hamstrings may be seen. Neurologic examination is generally normal. There is often well-localized tenderness to deep palpation just lateral to the involved spinous process.

The diagnosis can be confirmed by finding a pars defect on an oblique lumbar spine radiograph. The defect is rarely seen on anteroposterior

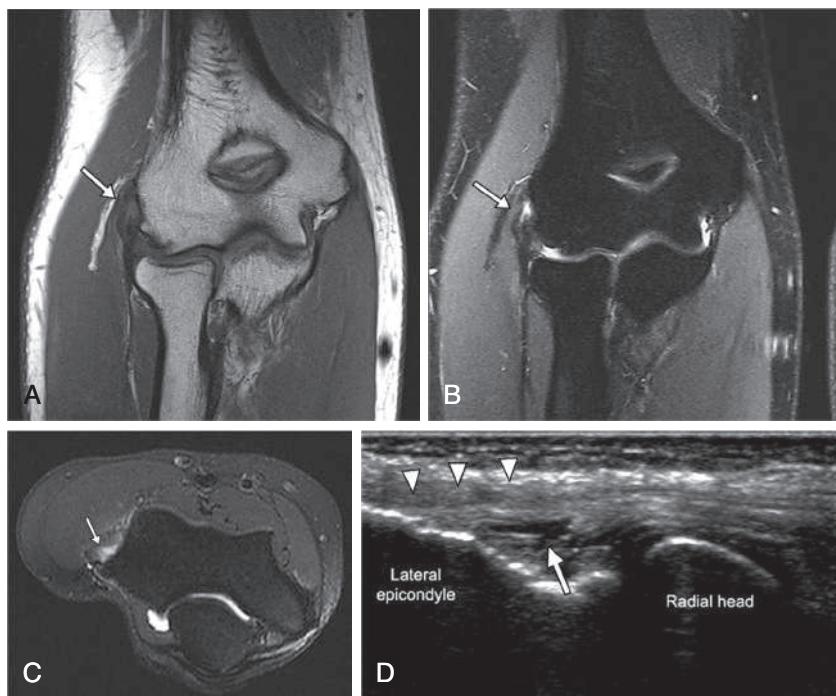


Fig. 728.11 A 22-yr-old tennis player with persistent lateral elbow pain despite 3 months of physical therapy. A, Coronal T1 sequence shows thickening and intermediate signal in the common extensor tendon (CET; arrow). B, Coronal T2 fat suppression (FS) (CET; arrow) and (C) axial proton density FS sequences reveal fluid signal within the CET and discontinuity of tendon fibers, consistent with a partial-thickness tear (CET; arrow). D, Corresponding long axis ultrasound image shows an anechoic fluid cleft (arrow) in the undersurface of the CET (arrowheads). (From Gustas CN, Lee KS. Current imaging concepts and image-guided treatments for the injured thrower's elbow. Radiol Clin N Am. 2016;54[5]:817–839. Fig. 2.)

(AP) and lateral views. MRI or bone single-photon emission CT (SPECT) is needed to confirm diagnosis if radiographs are normal and spondylolysis is suspected. A plain CT scan can help identify the degree of bony involvement and is sometimes used to assess healing.

Treatment includes pain relief and activity restriction. Rehabilitation consisting of trunk strengthening, hip flexor stretching, and hamstring stretching is important in most cases. A thoracic lumbar sacral orthotic may be considered for symptom management in cases in which conservative measures fail, but the overall benefit of bracing on healing is unclear.

Spondylolisthesis and Facet Syndrome

Spondylolysis, spondylolisthesis, and facet syndrome are injuries to the posterior elements of the vertebrae. Spondylolisthesis occurs when bilateral pars defects exist and forward displacement or slippage of a vertebra occurs upon the vertebra inferior to it (see Chapter 720.6). Facet syndrome has history and physical examination findings similar to those of spondylolysis. It is caused by instability or injury to the facet joint, posterior to the pars interarticularis and at the interface of the inferior and superior articulating processes. Facet syndrome can be established by identifying facet abnormalities on CT or by exclusion, if a radiograph and MRI rule out spondylolysis.

Treatment of posterior element injuries is conservative and directed at reducing the extension-loading activity, often for 2–3 months. Body mechanics, posture principals, core strengthening, and lumbar pelvic stabilization routines can be very helpful in the functional recovery of the motivated athlete. Walking, swimming, and cycling can be appropriate exercises during the rehabilitation phase. Rarely, spinal segmental fusion can be indicated in the athlete with spondylolisthesis and persistent symptomatic segmental instability despite conservative care.

LUMBAR DISK HERNIATION, STRAIN, AND CONTUSION

Intervertebral disk injury in children and adolescents is uncommon. Symptoms include pain with prolonged standing and prolonged periods of lumbar flexion, such as sitting in a car. Presentation is variable,

and patients may report an acute pain onset with an obvious inciting event or an insidious onset with a history of heavy lifting or repetitive axial load activities. In contrast to the selective motor and sensory deficits often observed in adults with disk herniation, athletes younger than 20 years of age less commonly have pain or tenderness over the course of the sciatic nerve. Physical examination findings may be minimal but usually include pain with forward flexion and lateral bending. It is unusual to have a positive straight leg test or any neurologic deficit in the young athlete with an injured disk. There may be tenderness of the vertebral spinous process at the level of the disk injury. A general aching sensation in the lower back or upper buttocks may be present. MRI usually confirms a clinical diagnosis. Assuming the herniation is not large and the pain is not intractable, treatment is conservative with analgesia and physical therapy. Surgery is rarely necessary.

Acute lumbar strain or contusion can be seen in the younger athlete and is usually associated with precipitating activity often outside of the normal routine. Physical examination reveals tenderness in the paraspinal and lateral soft tissues often associated with recreating the mechanism of injury. Thoracic and lumbar strain in the school-age child is frequently associated with obesity, deconditioning, positive family history, and poorly supervised and equipped recreational activity. Up to 20% of youths have experienced back pain at some point in their life before the age of 15 years. The backpack is the most common cause of back pain of a benign nature in children, with up to 74% of school backpack-wearers experiencing pain. Back pain is more common with the heavy backpack (>10–20% of body weight), female sex, large body mass index, and single shoulder strap.

Treatment is conservative and includes analgesia, myofascial release, massage, and physical therapy, as tolerated. The natural history of acute back strain in adults is that 50% are better in 1 week, 80% in 1 month, and 90% in 2 months, regardless of therapy. The course of back pain in young athletes is likely similar given the elimination of obvious precipitating influence and/or activities, as discussed previously.

Sacroiliitis manifests as pain over the sacroiliac joints; it is usually chronic but is occasionally associated with a history of trauma. Patients

have a positive result with the **Patrick test**, performed in the supine position by resting the foot of the affected side across the opposite knee (“figure-4” position), stabilizing the contralateral iliac crest, and externally rotating the hip on the affected side (pushing the knee down and lateral). Symptomatic improvement with knee-to-chest maneuvers and subsequent posterior pelvic tilt may be present. A radiograph of the sacroiliac joints is indicated, and if results are positive, exploration for a rheumatologic disease (ankylosing spondylitis [see Chapter 197], juvenile idiopathic arthritis [see Chapter 196], or inflammatory bowel disease [see Chapter 382]) is warranted.

Treatment is with relative rest, NSAIDs, and physical therapy. Ankylosing spondylitis is more likely if the onset of lower back pain is before 40 years of age, if there is morning stiffness demonstrating improvement with activity, a family history is present, there is clear benefit from antiinflammatory medication, and if the pain has a gradual onset having lasted longer than 3 months.

OTHER CAUSES

Non-sports-related causes of low back pain in the young athlete are numerous and include infection (osteomyelitis, diskitis) and neoplasia (see Chapter 720.5). These should be considered in patients with fever, weight loss, other constitutional signs, or lack of response to initial therapy. Osteomyelitis of the lower back or pelvis is often, but not always, associated with fever. Undiagnosed Scheuermann disease needs to be considered with a history of chronic back pain; it is more common in males and younger adolescents and should be distinguished from symptomatic postural roundback and congenital decompensating kyphosis. Atypical Scheuermann disease or thoracolumbar apophysitis can progress and become the pediatric equivalent of an adult compression fracture. Benign tumors of the spine include osteoid osteoma, which presents with intense focal nighttime pain that is not activity related and is almost always relieved by aspirin or NSAIDs. Undiagnosed osteoblastoma, eosinophilic granuloma, aneurysmal bone cyst, and fibrous dysplasia are additional benign tumors not to be excluded. Malignant spinal tumors include Ewing sarcoma (onion skin appearance) and osteogenic sarcoma (sunburst pattern); both are associated with the *Codman triangle*, which is the triangular area of new subperiosteal bone seen on radiographs when a tumor raises the periosteum away from the bone. Metastatic tumors of the spine include neuroblastoma, spinal cord tumors, leukemia, and lymphoma. Wilms tumor can also metastasize to the spine and be associated with hemihypertrophy. Referred pain to the spine always needs to be considered. Conditions that can refer pain include pyelonephritis, renal osteodystrophy, pneumonia, endocarditis, cholecystitis, nephrolithiasis, pancreatitis, megacolon, constipation/ileus, hiatal hernia/reflux, pelvic inflammatory disease, and sickle cell crisis. Undiagnosed pregnancy is a consideration in the age-appropriate female. Psychogenic pain and fibromyalgia can be seen in children. Child abuse can present in the spine, with soft tissue injuries more common than fractures. Posterior rib and spinous process fractures can be seen in up to 30% of abused children.

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728.5 Hip and Pelvis Injuries

Gregory L. Landry and Andrew M. Watson

Injuries to the hip and pelvis represent a small percentage of sports injuries, but they are potentially severe and require prompt diagnosis. Hip pathology can manifest as knee pain with normal findings on knee examination.

In children, **transient synovitis** (see Chapter 719.2) is the most common nontraumatic cause of hip pain. It usually manifests with acute onset of a limp, with the child refusing to use the affected leg and painful range of motion on examination. There may be a history of minor trauma or a recent viral infection. This is a self-limiting condition that usually resolves in 48–72 hours.

Legg-Calvé-Perthes disease (avascular necrosis of the femoral head) also presents in childhood with insidious onset of limp and hip pain (see Chapter 719.3).

Until skeletal maturity (Table 728.2), younger athletes are susceptible to apophyseal injuries (e.g., the anterior superior iliac spine). **Apophysitis** develops from overuse or from direct trauma. **Avulsion fractures** occur in adolescents playing sports requiring sudden, explosive bursts of speed (see Fig. 728.2). Large muscles contract and create force greater than the strength of the attachment of the muscle to the apophysis. Biomechanical susceptibility of the pelvis allows separation to occur in the cartilaginous region between the apophysis and the adjoining bone. The most common sites of pelvic avulsion fractures are the anterior superior iliac spine (sartorius and tensor fasciae lata), anterior inferior iliac spine (rectus femoris), lesser femoral trochanter (iliopsoas), ischial tuberosity (hamstrings), and the iliac crest (abdominal muscles). Symptoms include localized pain and swelling with decreased strength and range of motion. Bilateral radiographs are important for comparison to assess for displacement, if any, of the fracture fragment. Significant displacement or the presence of a large fragment may require orthopedic consultation. Initial treatment includes ice, analgesics, rest, and pain-free range of motion exercises. Crutches are usually needed initially for ambulation. Surgery is not typically indicated because most of these fractures—even large or displaced ones—heal well. Direct contact to the bone around the hip and pelvis causes exquisitely tender subperiosteal hematomas called “**hip pointers**.” These injuries are more commonly seen around the anterior superior iliac spine and the iliac crest. Limited active range of motion can be identified about the hip, brought on by contracture of locally attached musculature such as hip flexors and hip abductors. Symptomatic care includes rest, ice, analgesia, and protection from re-injury.

Slipped capital femoral epiphysis usually occurs among 11- to 15-year-olds during the time of rapid linear bone growth (see Chapter 719.4) and often presents with complaints of pain in the groin area or, on occasion, referred pain felt at the knee. Bilateral hip radiographs confirm the diagnosis.

A **femoral neck stress fracture** can manifest as vague progressive hip pain in an endurance athlete. Females are at higher risk. This diagnosis should be suspected in the running athlete with vague anterior

Table 728.2 Age of Appearance and Fusion of Apophyses in Hip and Pelvis

APOPHYSES	APPEARANCE (YR)	FUSION (YR)	RELATED MUSCLE GROUP(S)
Anterior inferior iliac spine	13–15	16–18	Quadriceps
Anterior superior iliac spine	13–15	21–25	Sartorius
Lesser trochanter	11–12	16–17	Iliopsoas
Greater trochanter	2–3	16–17	Gluteal
Ischial tuberosity	13–15	20–25	Hamstrings
Iliac crest	13–15	21–25	Abdominal obliques Latissimus dorsi

thigh pain without a history of trauma or acute injury. On examination, there may be pain with passive stretch of the hip flexors and pain with hip rotation. If radiographs do not demonstrate a periosteal reaction consistent with a stress fracture, MRI may be indicated to confirm the suspected diagnosis and determine the location of the fracture. Orthopedic consultation is necessary in femoral neck stress fractures because of their predisposition to nonunion and displacement with minor trauma or continued weight-bearing. These fractures carry increased risk of avascular necrosis of the femoral head. Whereas compression (inferomedial) side femoral neck stress fractures can typically be treated conservatively with non-weight-bearing, tension side (superolateral femoral neck) fractures may be at particular risk of progression and often require surgical fixation.

Osteitis pubis is an inflammation at the pubic symphysis that may be caused by excessive side-to-side rocking of the pelvis. It can be seen in an athlete in any running sport and is more common in sports requiring additional use of the adductor muscles such as ice hockey, soccer, and inline skating. Athletes typically present with vague groin pain that may be unilateral or bilateral. On physical examination, there is tenderness over the symphysis and sometimes over the proximal adductors. Adduction strength testing causes discomfort. Radiographic evidence (irregularity, sclerosis, widening of the pubic symphysis with osteolysis) may not be present until symptoms are present for 6–8 weeks; MRI is more sensitive to early changes. Relative rest for 6–12 weeks may be required. Some patients require corticosteroid injection as adjunctive therapy. Ultrasound needle guidance may be used to improve the accuracy of the injection while simultaneously avoiding injury to surrounding structures, such as the bladder, and vascular structures of the genitalia.

Acetabular labrum tears can occur in the hip, similar to glenoid labrum tears in the shoulder. Athletes may have a history of trauma and complain of sharp anterior hip pain associated with a clicking or catching sensation. Clinical diagnosis is often difficult; magnetic resonance arthrography is the gold standard for diagnosis, but MRI may be useful as well.

Snapping hip syndrome is caused by the iliopsoas musculotendinous unit riding over the pectenial eminence of the pelvis, anterior hip capsule, or the iliotibial band (ITB) over the greater trochanter. Lack of flexibility in these muscles results in snapping, as the musculotendinous unit slides over the associated bony prominence. It is most commonly seen in ballet dancers and runners, and it can occur as an acute or, more commonly, overuse injury. Athletes present with either a painful or painless click or snap in the hip, usually located lateral or anterior and deep within the joint. Examination often reproduces the symptoms. Radiographs are not usually needed in the workup. Ultrasound examination can be useful to visualize the anatomic structures in question causing the snapping sensation. Core weakness may be present, leading to excessive movement about the hip girdle contributing to increased sliding of the tight muscle over the boney prominence. Treatment involves analgesia, relative rest, biomechanical assessment, core flexibility, and stretching/strengthening of the involved soft tissue. Patients with concomitant greater trochanteric bursitis may benefit from a corticosteroid injection into the inflamed bursa to improve pain control and facilitate rehabilitation. The athlete may return to activity as tolerated. Common soft tissue injuries around the hip and pelvis include strain and tendinosis of the hip flexors (groin) and hamstrings in addition to quadriceps contusions and greater trochanteric bursitis.

The term **athletic pubalgia** is commonly used to describe a number of different pathologies that may cause lower abdominal or groin pain. Often called a sports hernia, this is a source of confusion as no true hernia exists through the inguinal canal or abdominal wall. The pathophysiology stems from tissue injury to the structures that comprise the pubic aponeurosis, most commonly the tendinous attachment of the abdominal and hip adductor musculature. Like a true hernia, pain may radiate into the anterior thigh, inguinal region, perineum, and/or scrotum. Physical exam may exhibit tenderness over, or adjacent to, the pubic ramus and/or reproduction of pain with resisted abdominal flexion or hip adduction. MRI, CT scan, and

bone scan can be helpful in ruling out other diagnoses but usually are negative. Some radiology departments may have MRI protocols specific for athletic pubalgia that provide more detailed imaging of the pathologic area. Patients who continue with symptoms despite conservative care, such as physical therapy, may be candidates for surgical intervention.

Femoroacetabular impingement (FAI) may coexist with athletic pubalgia to produce groin pain. FAI is defined as an abnormal contact between the femoral neck and the acetabulum as a result of excessive bone on the acetabular rim, the femoral neck, or both. X-rays and MRI can be diagnostic. As in athletic pubalgia, a period of rest and rehabilitation should be attempted, and those who fail conservative treatment should be referred to a sports medicine specialist.

Undiagnosed **non-sports-related conditions** need to be considered. Differential diagnoses may include the epiphyseal dysplasias, congenital or developmental hip dysplasia, additional causes of avascular necrosis, including sickle cell disease, Gaucher disease, rheumatoid arthritis, and other collagen disorders and steroid therapy. Inguinal hernia should be recognized in those patients with groin pain exacerbated with coughing/Valsalva maneuver and a palpable mass in the groin. Traumatic hip dislocations are relatively rare in children but should not be overlooked. Leg-length discrepancies (usually >1 cm) can be symptomatic at the hip in an otherwise healthy child. Common tumors in the lower extremities include osteosarcoma along with osteoblastoma, aneurysmal bone cysts, and fibrous dysplasia (more common in the pelvis). Metastatic tumors to the lower extremities include neuroblastoma, lymphoma, and leukemic infiltration with joint arthralgia. Child abuse always needs to be considered in a young patient with musculoskeletal pain.

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728.6 Knee Injuries

Gregory L. Landry and Andrew M. Watson

Knee pain is common among adolescents. Acute knee injuries that cause immediate disability and/or effusion are likely to be due to fracture, patellar dislocation, anterior or posterior cruciate ligament injury, or meniscal tear. The mechanism of injury is usually a weight-bearing event. Physeal injuries tend to predominate in younger patients, whereas more skeletally mature adolescents tend to sustain ligamentous injuries. If the knee swells more immediately (within several hours of injury), the swelling is likely caused by a hemarthrosis and more severe injury. The injury most likely to occur with a hemarthrosis is an **anterior cruciate ligament** (ACL) injury. This injury (rare in children younger than 12 years) is usually caused by direct contact, landing off-balance from a jump, quickly changing direction while running, or hyperextension. Instability is often present but may be hard to detect in the presence of significant swelling. Females are more than twice as likely as males to disrupt their ACL, often during sports such as basketball or soccer. Occasionally, these injuries are associated with an avulsion injury of the anterior tibial spine. Most athletes with significant ACL injury need orthopedic consultation with consideration of ACL reconstruction. Chronic ACL insufficiency may increase the risk of meniscal injury, early osteoarthritis, and further joint dysfunction. Physeal-sparing reconstructions with minimal risk of growth arrest or angular deformity have been reported with success in children younger than 12 years and adolescents.

Posterior cruciate ligament (PCL) injury occurs from a direct blow to the region of the proximal tibia when the knee is flexed, such as might occur with a dashboard injury or a fall to the knees in volleyball. PCL injuries are rare and are usually treated nonsurgically.

Medial collateral ligament injuries typically result from a valgus blow to the outside of the knee. Isolated **lateral collateral ligament** injuries are uncommon and result from significant varus knee stress. Because they are extra-articular, lateral collateral and medial collateral ligament injuries should not produce a significant knee effusion and

are generally less disabling. Isolated medial and lateral collateral injuries are generally managed nonsurgically with conservative care and appropriate rehabilitation.

Meniscal tears generally occur by the same mechanisms as ACL injuries. They are often associated with less hemarthrosis, significant joint line pain, and increased pain with full knee flexion. MRI will usually yield the diagnosis; conservative care, including PRICE principles, is therapeutic for smaller injuries. Orthopedic consultation is indicated for meniscus tears in children and adolescents, and surgery may be indicated for larger tears, displaced tears, or those not healing with conservative care over 6–8 weeks. An isolated meniscal tear in a child younger than 10 years of age is unusual. The surgical choice is often repair of the meniscus rather than resection because of the increased potential in children for cartilaginous healing. Discoid meniscus (an anatomic variant covering lateral tibial plateau) should be considered in children younger than 12 years of age and those with a suspected meniscus injury without a history of notable trauma.

Patellar dislocation occurs most often as a noncontact injury when the quadriceps muscles forcefully contract to extend the knee while the tibia is externally rotated in relation to the femur. Patellar dislocation is the second most common cause of hemarthrosis. The patella is almost always dislocated laterally, and this motion tears the medial patellar retinaculum, causing bleeding in the joint. Recurrent episodes of patellar instability are associated with less swelling. Patellar dislocations are often associated with genu valgum, external tibial torsion, and general ligamentous hyperlaxity. Exercises to strengthen the quadriceps, particularly the vastus medialis, and the use of patella-tracking braces may be helpful. Recurrent instability can require surgical intervention. Surgical stabilization of the medial patellar tissues and lateral retinacular release can be helpful in more difficult cases.

INITIAL TREATMENT OF ACUTE KNEE INJURIES

The physician should inspect for an effusion and obvious deformities; if any deformity is present, the physician should assess neurovascular status and transfer the patient for emergency care as indicated. If no gross deformities are present and neurovascular integrity is intact, initial maneuvers include full passive extension and gentle valgus and varus stress to the knee while in extension. *Any laxity to varus or valgus stress in full extension implies a multiligamentous injury.* Comparison to the noninjured knee is always helpful for assessing degrees of laxity and range of motion. The patient's ability to contract the quadriceps should be noted. Pain occurring with quadriceps contraction, or the inability to contract the quadriceps muscle, implies an injury to the extensor mechanism. Tenderness over the medial patella, medial retinaculum, or above the adductor tubercle is associated with a patellar dislocation (usually lateral). Point tenderness is consistent with fracture or injury to the underlying structure. Meniscal tears usually manifest as tenderness along the joint line, accentuated with flexion of the knee beyond 90 degrees. Pain or limitation in either flexion or extension while rotating the tibia implies a meniscal injury. Ligament injury is manifested as pain or laxity with the appropriate maneuver (Fig. 728.12).

If a patient cannot weight-bear without pain, or has clinical signs of instability, significant swelling, or any other major concern, the knee should be immobilized and crutches provided. The Ottawa knee rule, which has been validated for children over 5 years of age, helps determine which patients with mild knee injuries require radiographs. X-rays should be obtained if *any* of the following apply: 55 years or older, point tenderness of fibular head, tenderness of the patella, inability to flex knee to 90 degrees, or inability to bear weight (inability to take four steps) both immediately after the injury and in the emergency department.

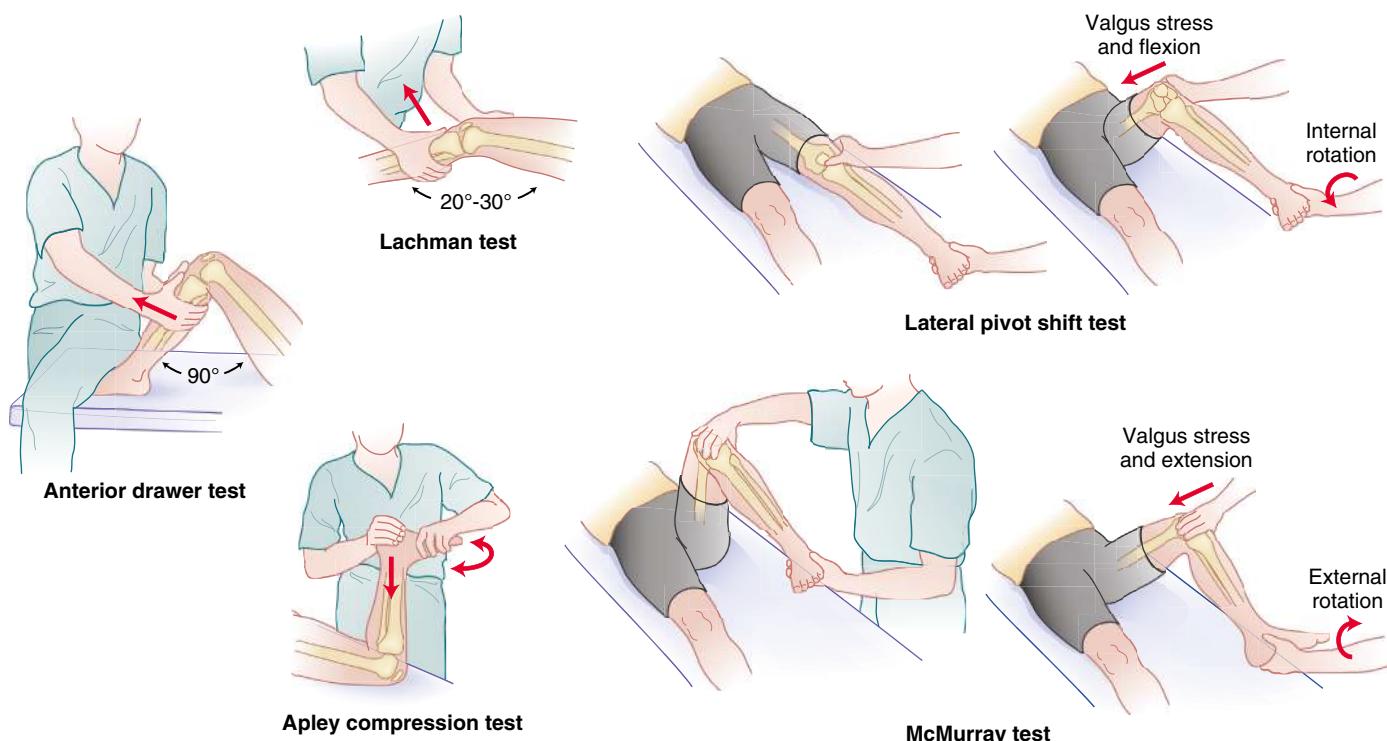


Fig. 728.12 Examination maneuvers include the Lachman, anterior drawer, lateral pivot shift, Apley compression, and McMurray tests. The Lachman test, performed to detect anterior cruciate ligament (ACL) injuries, is conducted with the patient supine and the knee flexed 20–30 degrees. The anterior drawer test detects ACL injuries and is performed with the patient supine and the knee in 90 degrees of flexion. The lateral pivot shift test is performed with the patient supine, the hip flexed 45 degrees, and the knee in full extension. Internal rotation is applied to the tibia while the knee is flexed to 40 degrees under a valgus stress (pushing the outside of the knee medially). The Apley compression test, used to assess meniscal integrity, is performed with the patient prone and the examiner's knee over the patient's posterior thigh. The tibia is externally rotated while a downward compressive force is applied over the tibia. The McMurray test, used to assess meniscal integrity, is performed with the patient supine and the examiner standing on the side of the affected knee.

If the patella is dislocated, reduction may be achieved with gentle active assistive knee extension. Straight-leg immobilizers offer no structural support and are only used for comfort and reminding the patient to be careful with any weight-bearing. A derotational hinge brace may be indicated for stabilization, such as after an injury involving both the ACL and medial collateral ligament. The leg should be elevated, and an elastic wrap can be applied for compression (PRICE principles).

CHRONIC INJURIES

Patellofemoral Stress Syndrome

Patellofemoral stress syndrome (PFSS), or runner's knee, is the most common cause of anterior knee pain. PFSS is also known as **patellofemoral pain syndrome** or **patellofemoral dysfunction** (see Chapter 718.5). It is a diagnosis of exclusion used to describe anterior knee pain that has no other identifiable pathology. Chondromalacia may be seen in association with softening of the articular cartilage underneath the patellar surface. Pain is usually difficult to localize. Patients indicate a diffuse area over the anterior knee as the source, or they might feel as if the pain is originating from underneath the patella. Bilateral pain is common, and pain is often worse going up stairs, after sitting for prolonged periods, or after squatting or running. There should be a negative history for significant swelling or true mechanical symptoms, which would indicate a more serious injury. History of change in activity is common, such as altered training surface or terrain, increased training regimen, or performance of new tasks.

Examination should include evaluation of stance and gait for lower limb alignment, musculature, and midfoot hyperpronation. Flexibility of the hamstrings, iliotibial band, and gastrocnemius should be assessed, because stress is increased across the patellofemoral joint when these structures are excessively tight. Hip range of motion should be assessed to rule out hip pathology. Medial patellar tenderness or pain with compression of the patellofemoral joint confirms the diagnosis in the absence of a significant effusion and other positive findings. PFSS is a clinical diagnosis usually managed without imaging.

Treatment focuses on assessing and improving flexibility, strength, and gait abnormalities. In the presence of midfoot hyperpronation (ankle valgus), new shoes or the use of arch supports can improve patellofemoral mechanics and alleviate pain. Ice and analgesics can be used to help control pain. Reduced overall activity or training is important initially in rehabilitation. Short arc quadriceps strengthening exercises can be helpful: active knee extension with or without resistance between 0 and 30 degrees of knee flexion. Hip and core strengthening exercises are also beneficial. Therapeutic taping techniques to improve patella tracking within the trochlear groove can be helpful with the assistance of a sports physical therapist. The use of a patellar stabilizing brace with a lateral buttress to maintain patellar alignment may be of benefit in more chronic cases as well.

Osgood-Schlatter Disease

Osgood-Schlatter disease is a traction apophysitis occurring at the insertion of the patellar tendon on the tibial tuberosity (see Chapter 718.4). Because it is also related to overuse of the extensor mechanism, Osgood-Schlatter disease is treated like PFSS. A protective pad to protect the tibial tubercle from direct trauma can be used. Therapeutic taping of the tibial tubercle may provide comfort, along with well-fitted knee sleeves and/or straps. NSAIDs are often prescribed for comfort. Stretching focused on the quadriceps and hamstrings is recommended, and PRICE principles apply. Patients and parents should be made aware that resolution is usually slow, often requiring 12–18 months. Complications are rare and can include growth arrest with recurvatum deformity and rupture or avulsion of the patellar tendon/tibial tubercle.

Other Chronic Injuries

Sinding-Larsen-Johansson disease is a traction apophysitis occurring at the inferior pole of the patella. It occurs most often in volleyball and basketball athletes. Treatment is similar to PFSS and Osgood-Schlatter disease.

Patellar tendinosis, or jumper's knee, is caused by repetitive microtrauma of the patellar tendon, usually at the inferior pole of the patella. In approximately 10% of cases, the quadriceps tendon above the patella is affected. It is associated with jumping sports but may occur in runners as well. Treatment is similar to that for PFSS, with an emphasis on eccentric strengthening in physical therapy. Relative rest is more important in patellar tendinosis because chronic pain can be associated with irreversible changes in the tendon. In these cases, recalcitrant to rest, activity modifications, and physical therapy, there may be a role of biologic injections such as platelet-rich plasma to the pathologic area. Surgical techniques also have a good success rate if needed.

Iliotibial band (ITB) friction syndrome is the most common cause of chronic lateral knee pain. Generally, it is not associated with swelling or instability. It is from friction of the ITB along the lateral knee, resulting in bursitis. Tenderness is elicited along the ITB as it courses over the lateral femoral condyle or at its insertion at Gerdy's tubercle along the lateral tibial plateau. Tightness of the ITB is also noted using the Ober test. To perform an Ober test, the athlete lies on one side, the inferior hip is flexed, and the superior hip is extended with the knee flexed. The examiner holds the superior foot in midair, and if the superior knee drops inferiorly toward the exam table, it implies a flexible ITB and a negative Ober test. If the knee and leg stay in midair, the Ober test is positive, suggesting a tight ITB. Treatment principles follow those for PFSS, except the emphasis is on improving flexibility of the ITB.

Other soft tissue injuries to be considered include prepatellar and pes anserine **bursitis**, plical syndromes, and Hoffa syndrome. The pes anserine bursa lies just under the conjoined tendon of the sartorius, gracilis, and semitendinosus muscles as it attaches medially to the proximal tibia. In **Hoffa syndrome**, the fat pad beneath the patella and posterior to the patella ligament becomes pinched with anterior pain on knee extension. These conditions are generally more common in adolescents, those with genu recurvatum, and long-distance runners. Undiagnosed non-sports-related conditions always need to be considered in the context of any child with a painful knee, particularly those younger than 12 years old. These include conditions such as OCD (see Chapter 718.3), which is most common on the lateral aspect of the medial femoral condyle. Inflammatory and infectious arthritis, Baker cyst (see Chapter 718.2), and hip pain referred to the knee are additional considerations. Tumors more common to the knee joint include osteogenic sarcoma (distal femoral and proximal tibial), Langerhans cell histiocytosis in the diaphysis, and eosinophilic granuloma in the epiphysis of long bones. Metastatic tumors to the lower extremities include neuroblastoma and lymphoma. As with any musculoskeletal injury in a child not responding to conservative care, more in-depth diagnostic pursuit for alternative pathology is mandatory.

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728.7 Lower Leg Exertional Pain: Shin Splints, Stress Fractures, and Chronic Compartment Syndrome

Gregory L. Landry and Andrew M. Watson

Stress injury to the bones of the lower leg occurs on a continuum from mild injury (shin splints) to stress fracture. All occur by an overuse mechanism.

Medial tibial stress syndrome, or shin splints, manifests with pain along the medial tibia and is the most common overuse injury of the lower leg. The pain initially appears toward the end of exercise, and if exercise continues without rehabilitation, the pain worsens and occurs earlier in the exercise period. There is diffuse tenderness over the lower third to half of the distal medial tibia. Any focal tenderness of the tibia is suspicious for a **tibial stress fracture**. A stress fracture tends to be associated with more severe pain and is painful during the entire workout. Shin splints and stress fractures represent a continuum of stress injury to the tibia and are thought to be related to traction of the soleus

on the tibia. Eccentric contraction of the medial aspect of the soleus is required to control pronation from initial contact to mid-stance with running. This contraction increases the stress of the fascial origin of the soleus, possibly through Sharpey fibers, causing disruption to the tibial periosteum and fibrocartilaginous attachments.

The diagnosis can be made by history and physical examination. Findings on plain radiographs of the tibia are typically unremarkable with shin splints, as well as with tibial stress fractures within the first 2 weeks of injury. Beyond this time frame, radiographs may demonstrate periosteal reaction if a stress fracture is present but may still be unremarkable. Sensitivity of plain radiographs can be increased by obtaining four views of the tibia: AP, lateral, and both oblique views. MRI is the most sensitive test to diagnose stress injuries as it can reveal both a stress fracture and stress reaction in the affected bone. Stress reactions may include bone marrow edema or periosteal reaction without a fracture line but represent an impending progression to a fracture if the offending stress is not reduced or eliminated.

The treatment of shin splints involves relative rest, correcting training errors, and addressing muscle imbalances and abnormal mechanical alignment. Orthotics and/or new shoes may be useful in patients who hyperpronate. Fitness can be maintained with non-weight-bearing activities, such as swimming, cycling, and water jogging. With shin splints, after 7–10 days, patients can usually start on the walk-jog program. If pain worsens, 2–3 pain-free days are required before resuming the walk-jog program. Ice should be used daily, and an analgesic should be used for pain control. Stretching the plantar flexors and hamstrings and strengthening the ankle dorsiflexors may be useful. Therapeutic taping and wrapping techniques to support the soft tissue attachments have been useful in some when directed by a skilled sports therapist. Being pain free for 7–10 days is recommended before exercises are commenced. Individuals with pain at rest and who are not responsive to treatment require continued evaluation for stress fracture. Treatment of tibial stress fractures is similar but requires more prolonged avoidance of running and jumping, usually 6–8 weeks.

Chronic compartment syndrome occurs in an athlete in a running sport, usually during a period of heavy training. It is caused by muscle hypertrophy and increased intracompartmental pressure with exercise. There is typically a pain-free period of about 10 minutes at the beginning of a workout before onset of constant throbbing pain that is difficult to localize. It lasts for minutes to hours after exercise and is relieved by ice and elevation. Classically, there is numbness of the foot associated with high pressure within the corresponding muscle compartment. The most common compartment affected is the anterolateral compartment with compression of the fibular nerve followed by the deep posterior compartment. The physical examination in the office is often normal, but weakness of the extensor hallucis longus (anterolateral compartment) and decreased sensation between the first and second toe may be present. Symptoms may be elicited through exercise in or near the examination room (jogging in place, stair climbing, etc.), and prompt evaluation after symptom onset may aid in diagnosis. Radiologic evaluation is typically negative and used primarily to rule out other conditions. Compartment pressure measurements are the test of choice. Treatment involves reduction of activity, antiinflammatory medication, orthotics (hyperpronation), heel cord stretching, light strengthening of distal musculature, optimal footwear, and cross-training (swimming, cycling, and water jogging). Cryotherapy and superficial heat can also be of help. Persistent symptoms, despite conservative care, may require fasciotomy.

Popliteal artery entrapment syndrome occurs when the popliteal artery is compressed by the medial head of the gastrocnemius muscle and the fascial band of the soleus with activity; the entrapment may be anatomic or functional (from hypertrophy). Patients may have claudication and paresthesia (involvement of the tibial nerve), and calf swelling (primary venous obstruction). Most patients have exertional leg pain with no symptoms at rest; pain may be unilateral or bilateral depending on the type of entrapment syndrome. The tibial or dorsalis pedis pulse may be reduced or absent with passive ankle dorsiflexion with the knee extended. Doppler exam in the neutral and flexion position confirms the diagnosis in most patients; magnetic resonance

angiography or CT angiography may be needed if the Doppler exam is inconclusive. Surgical correction is the treatment of choice and involves medial gastrocnemius fasciotomy, take down of the soleus tibial attachments, and resection of the fibula soleus band. If the artery is injured, it requires bypass surgery.

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728.8 Ankle Injuries

Gregory L. Landry and Andrew M. Watson

Ankle injuries are the most common acute athletic injury. Approximately 85% of ankle injuries are ankle sprains, and 85% of these are inversion injuries (foot planted with the lateral fibula moving toward the ground), 5% are eversion injuries (foot planted with the medial malleolus moving toward the ground), and 10% are combined.

EXAMINATION AND INJURY GRADING SCALE

In obvious cases of fracture or dislocation, evaluating neurovascular status with as little movement as possible is the initial priority. If no deformity is obvious, the next step is inspection for edema, ecchymosis, and anatomic variants. Key sites to palpate for tenderness are the entire length of the fibula; the medial malleolus; the base of the fifth metatarsal; the anterior, medial, and lateral joint lines; the navicular; and the Achilles tendon complex. Assessment of active range of motion (patient alone) in dorsiflexion, plantar flexion, inversion, and eversion along with gentle resisted range of motion can be helpful.

Provocative testing attempts to evaluate the integrity of the ligaments. In a patient with a markedly swollen, painful ankle, provocative testing is difficult because of muscle spasm and involuntary guarding. It is more useful on the field before much bleeding and edema have occurred. The anterior drawer test assesses for anterior translation of the talus and competence of the anterior talofibular ligament. The inversion stress test examines the competence of the anterior talofibular and calcaneofibular ligaments (Fig. 728.13). In the acute setting, the integrity of the tibiofibular ligaments and syndesmosis can be examined by the syndesmosis squeeze test. Pain at the ankle joint with squeezing the superior aspect of the lower leg implies injury to the interosseous membrane and syndesmosis between the tibia and fibula—suspicious for a high ankle sprain or more severe injury. Athletes with this injury cannot bear any weight and have severe pain with dorsiflexion and external rotation of the foot. Occasionally, the peroneal tendon dislocates from the fibular groove simultaneously with an ankle sprain. To assess for peroneal tendon instability, the examiner applies pressure from behind the peroneal tendon with resisted eversion and plantar

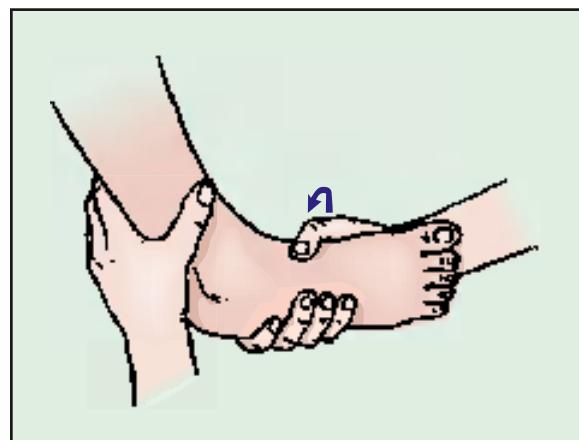


Fig. 728.13 Inversion stress tilt test for ankle instability. (From Hergenroeder AC. Diagnosis and treatment of ankle sprains: a review. Am J Dis Child. 1990;144:809–814.)

flexion, and the tendon pops anteriorly. If either a significant syndesmotic injury or an acute peroneal dislocation is suspected, orthopedic consultation should be sought.

RADIOGRAPHS

AP, lateral, and mortise views of the ankle are obtained when patients have pain in the area of the malleoli, are unable to bear weight, or have focal bone tenderness over the distal tibia or fibula. The **Ottawa ankle rules** help define who requires radiographs (Fig. 728.14). A foot series (AP, lateral, and oblique views) should be obtained when patients have pain in the area of the midfoot or bone tenderness over the navicular or fifth metatarsal, and/or an inability to bear weight. It is important to differentiate an **avulsion fracture** of the fifth metatarsal base (dancer's fracture) from the more distal **Jones fracture** of the proximal fifth metatarsal (located about 2 cm distal to the proximal end). The former is treated like an ankle sprain; the latter fracture has an increased risk of nonunion and requires orthopedic consultation. Injury to the deltoid ligament of the medial ankle is rare but should raise the question of proximal fibular fracture. In this circumstance more proximal tibial imaging may be necessary. A **talar dome fracture** may present as an ankle sprain that does not improve. Radiographs on initial presentation can have subtle abnormalities. Any suspicion on the initial radiographs of a talar dome fracture warrants orthopedic consultation and further imaging. In the early adolescent, always look carefully at the tibial epiphysis. Nondisplaced Salter III fractures can be subtle and need to be recognized early and referred to an orthopedic surgeon promptly. Diagnostic ultrasound, when available at the point of care, can efficiently provide prognostic information by direct visualization of injured ligaments. Additionally, dynamic stress can be applied during ligament visualization to assess for gaping of the joint, which is indicative of more complete tearing with an increased duration of expected recovery.

INITIAL TREATMENT OF ANKLE SPRAINS

Ankle sprains need to be treated with PRICE principles. This should be followed for the first 48–72 hours after the injury to minimize bleeding and edema. For an ankle injury, this may consist of crutches and an elastic wrap, although other compression devices, such as an air stirrup splint, are also effective. This allows early weight-bearing with protection and can be removed for rehabilitation. It is important to start a rehabilitation program as soon as possible.

Rehabilitation

Rehabilitation should begin the day of injury; for patients who have pain with movement, isometric strengthening can be started. Early-phase intervention includes restoration of functional range of motion, strengthening with emphasis on peroneal musculature, and early sensory proprioceptive training. Later intervention includes higher-level balance activities, advanced proprioception exercises, and endurance training. When determining when an athlete is ready for running, there must be full range of motion and nearly full strength compared to the uninjured side. While standing on the uninjured side only, the athlete is instructed to hop 8–10 times, if possible. When this can be achieved without pain on the injured side, the athlete can begin to run, starting out with jogging and gradually progressing in speed. The athlete must stop if there is significant pain or limp. Finally, before returning to sport, the athlete must be able to sprint and change directions off the injured ankle comfortably. Performing some sport-related tasks is also helpful in determining readiness for return to play.

Recurrent ankle injuries are more likely in patients who have not undergone complete rehabilitation. Ankle sprains are less likely in players wearing high-top shoes or lace-up ankle braces. Proper taping of the ankle with adhesive tape can provide functional support but loosens with use and is often unavailable. Surgery is a consideration for chronic mechanical instability with lateral complex ligamentous laxity in the failure of more conservative care. Salter-Harris grade I distal fibular fractures need careful consideration, particularly in the child younger than 12 years of age. The physeal plates are generally the weakest link in the musculoskeletal chain and tend to slide or pull apart before the surrounding soft tissue and/or ligaments tear in this younger population.

OTHER CAUSES OF ANKLE PAIN

Toddler's fracture needs to be considered in young children with ankle pain, especially in those younger than 6 years (see Chapter 724.4). The proposed mechanism involves sheer stress with lack of displacement because of the periosteum that is relatively strong compared to the elastic bone in younger children. Initial radiographs may be inconspicuous (a faint spiral oblique line) or even normal. The condition can be mistaken for osteomyelitis, transient synovitis, or even child abuse. Toddler's fracture usually occurs in the lower third of the tibia, whereas nonaccidental injury typically affects the upper two-thirds or midshaft

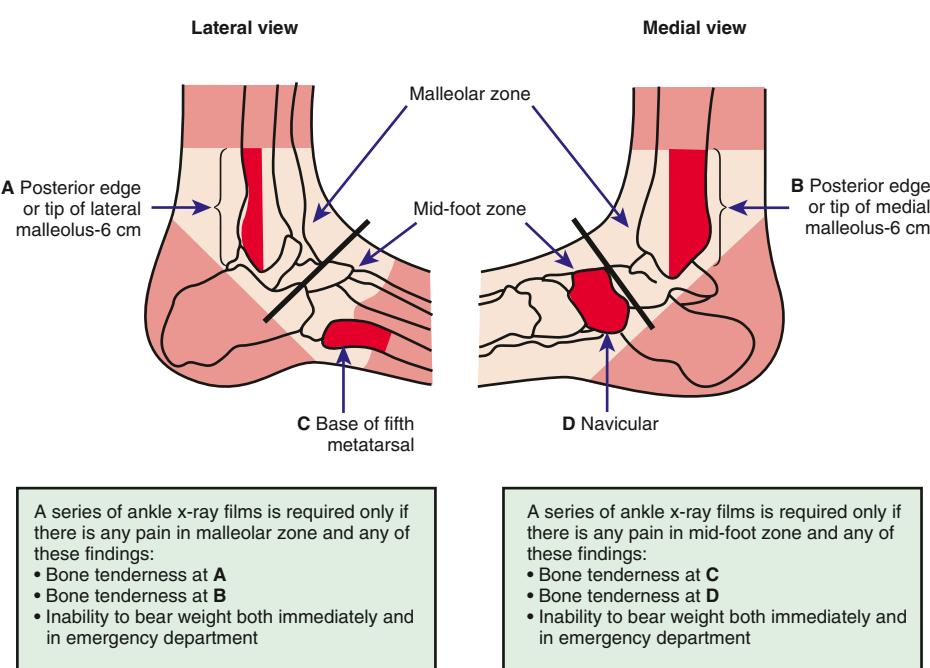


Fig. 728.14 Ottawa ankle rules. (From Bachmann LM, Kolb E, Koller MT, et al. Accuracy of Ottawa ankle rules to exclude fractures of the ankle and mid-foot; systematic review. BMJ. 2003;326:417–419.)

of the tibia. Other less common conditions that cannot be excluded include os fibulare, a congenital unfused secondary ossification center of the distal fibula. This can be seen in younger patients with recurrent ankle sprains, particularly as their body weight and activity increase during the early academic years. Undiagnosed tarsal coalitions can also be seen in the presence of ankle sprains in younger children (most commonly talocalcaneal and calcaneal navicular). Muscular strains and/or tendinoses are more prevalent in the older child and adolescent, and include peroneal, posterior tibialis, and gastrocnemius/Achilles types. Tarsal tunnel syndrome (entrapment of the posterior tibial nerve) is more prevalent in the adolescent/younger adult and is commonly associated with medial ankle pain and burning or tingling into the sole of the foot.

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728.9 Foot Injuries

Gregory L. Landry and Andrew M. Watson

Metatarsal stress fractures can occur in any running athlete. The history is often one of insidious pain with activity that is getting worse. Examination reveals point tenderness over the mid-shaft of the metatarsal, most commonly the second or third metatarsal. Radiographs might not show the periosteal reaction before pain has been present for 2 weeks or more. Treatment is relative rest for 6–8 weeks. Shoes with good arch supports reduce stress to the metatarsals.

Vague dorsal foot pain in an athlete in a running sport can represent a **navicular stress fracture**. Unlike other stress fractures, it might not localize well on examination. If there is any tenderness around the navicular, a stress fracture should be suspected. This stress fracture can take many weeks to show up on plain radiographs, so MRI should be done to confirm the diagnosis. Because this fracture is at high risk of nonunion, immobilization and non-weight-bearing for 8–12 weeks is the usual treatment. A CT scan should be obtained to document full healing after the period of immobilization.

Sever disease (calcaneal apophysitis) occurs at the insertion of the Achilles tendon on the calcaneus and manifests as activity-related pain (see Fig. 728.3). It is more common in males, is often bilateral, and usually occurs between ages 8 and 13 years. Tenderness is elicited at the insertion of the Achilles tendon into the calcaneus, especially with squeezing the heel (positive squeeze test). Sever disease is associated with tight Achilles tendons and mid-foot hyperpronation that puts more stress on the plantar flexors of the foot. Treatment includes relative rest, ice, massage, stretching, and strengthening the Achilles tendon. Correcting the mid-foot hyperpronation with orthotics, arch supports, or stabilizing shoe wear is important in most athletes with Sever disease. If the foot is neutral or there is mild hyperpronation, cushioned heel lifts can be helpful to unload the Achilles tendon and its insertion. With optimal management, symptoms frequently improve in 4–8 weeks. Generally, if there is no limp during the athletic activity, young athletes with Sever disease should be allowed to play.

Plantar fasciitis is an overuse injury resulting in degeneration of the plantar aponeurosis. Rare in prepubertal children, this diagnosis is more likely seen in the adolescent or young adult. Athletes report heel pain with activity that is worse with the first steps of the day or after several hours of non-weight-bearing. Tenderness is elicited on the medial calcaneal tuberosity. Relative rest from weight-bearing activity is helpful. Athletes get plantar fasciitis when shoes are worn with inadequate arch supports. New shoes or use of semirigid arch supports often lessen the pain. Stretching the calves and plantar fascia helps, assisted at times with therapeutic ultrasound treatment. Some patients benefit from night splints even though they can make sleep difficult. As long as there is no limping with athletic activity, the athlete may continue participation. Complete recovery is usually seen at 6 months.

Corticosteroid injection, extracorporeal shock-wave therapy, or injections of platelet-rich plasma can be considered in those cases recalcitrant to conservative treatments.

Calcaneal stress fracture is seen in the older adolescent or young adult involved in a running sport. There is heel pain with any weight-bearing activity. The physical examination reveals pain with squeezing the calcaneus. Sclerosis can show up on the AP and lateral radiographs after 2–3 weeks of pain. MRI may need to be performed to confirm the diagnosis in some cases. The calcaneus is an uncommon location for a stress fracture and is often associated with osteopenia. Treatment is rest from running and other weight-bearing activity for at least 8 weeks. Immobilization is rarely necessary.

Pes planus, or “flat feet,” may be termed “flexible” or “rigid.” Flexible pes planus is usually asymptomatic and is the most common type found in children (see Chapter 715.5). Foot orthotics may be helpful for older children with foot pain or associated muscle cramping. Rigid pes planus is a congenital deformity associated with other anomalies in 50% of cases. It is caused by failure of the tarsal bones to separate, leaving a bony cartilaginous or fibrous bridge or coalition between two or more tarsal bones (see Chapter 715.6). Talocalcaneal coalitions are more symptomatic between 12 and 16 years of age, whereas calcaneonavicular coalitions are more symptomatic between 8 and 12 years of age. Symptoms are insidious with occasional acute arch, ankle, and mid-foot pain, which is at times brought on with sports-related activities. The hindfoot often does not align in its normal varus position on tiptoe maneuvers. Patients are predisposed to ankle sprains secondary to limited subtalar motion, and stress to the subtalar and transverse tarsal joints frequently causes pain. CT scans are diagnostic, and initial treatment is conservative with short leg casting and/or molded orthoses and rest. In the case of failure of conservative care, surgical intervention is usually necessary. Rigid cavus feet can also be associated with metatarsalgia, clawing, and intrinsic muscle atrophy, which are all possible in the young athlete (see Chapter 715.7). With a cavus foot, undiagnosed neurologic conditions, such as Charcot-Marie-Tooth disease, spinal dysraphism, Friedrich ataxia, or spinal tumor, need to be considered. Custom-molded orthotics may be helpful, and family history can be critical. Symptomatic, accessory navicular bones and sesamoiditis can be considered when these areas are painful and do not have evidence of fracture or prior trauma. These conditions are more common in the adolescent or younger adult and can be exacerbated with sporting activities.

Other conditions causing foot pain include **Lisfranc sprain** and/or dislocation, which is more common in football linemen or other athletes requiring heavy loading on the mid-foot and forefoot joints, and gymnasts using the balance beam. The Lisfranc joint is the tarsal metatarsal articulation of the three cuneiform bones and the cuboid with the five proximal metatarsals. Turf toe can be seen, particularly in the older child and/or adolescent running on artificial or synthetic surfaces. It results from hyperextension through the first metatarsal phalangeal joint, spraining the ligaments surrounding the joint often in a football and/or soccer activity.

Isein apophysitis is an apophysitis that occurs at the tuberosity of the fifth metatarsal. The apophysis at this site appears between the ages of 9 and 14 years and is located within the insertion of the peroneus brevis tendon. This condition can be a predisposing factor to dancer's fracture (see Chapter 728.8). **Freiberg disease**, which involves the collapse of the articular surface and subchondral bone, usually of the second metatarsal, and **Kohler disease**, which involves irregular ossification of the tarsal navicular joint with localized pain and increased density, should always be considered in the evaluation **osteochondroses of the foot** (see Chapter 715.8). Freiberg disease is more common in girls between the ages of 12 and 15 years, whereas Kohler disease occurs in younger individuals, age 2–9 years, and is frequently reversible with conservative care, including orthoses and casting.

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Chapter 729

Sports-Related Traumatic Brain Injury (Concussion)

Alex M. Taylor, William P. Meehan III, and Mark R. Proctor

Concussion is a form of **traumatic brain injury** (TBI) caused by sudden acceleration, deceleration, or rotational forces to the brain, which can occur with a blow to the head, neck, face, or body. The resulting pathophysiologic state is associated with a constellation of signs and symptoms that, for **sport-related concussions** (SRCs), typically self-resolve within 7–10 days. A minority of children can experience **persistent postconcussion symptoms** (PPCS) that extend beyond 28 days and limit functional ability, cause social isolation, reduce school attendance and performance, and can lead to anxiety, mood alteration, and lower quality of life. Accurate diagnosis and appropriate management of concussion is needed to safely return children to school and sports and to avoid the potential for worse outcomes.

DEFINITION/TERMINOLOGY

The spectrum of TBI ranges from mild to severe. Classification is typically determined by score on the Glasgow Coma Scale (see Chapter 79), with severe = ≤ 8 , moderate = 9–12, and mild = 13–15. Although concussion and **mild TBI (mTBI)** are sometimes used interchangeably, concussion may be best understood as the *clinical syndrome* that is associated with mTBI. There are several agreed-on features:

- ◆ Concussion may be caused by a direct blow to the head, face, neck, or elsewhere on the body with an “impulsive” force transmitted to the head.
- ◆ Concussion typically results in the rapid onset of short-lived impairment of neurologic function that resolves spontaneously. However, in some cases, signs and symptoms may evolve over minutes to hours.
- ◆ Concussion may result in neuropathologic changes, but the acute clinical signs and symptoms largely reflect a *functional* disturbance rather than a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies.
- ◆ Concussion results in a range of clinical signs and symptoms that may or may not involve loss of consciousness (Fig. 729.1). Resolution of the clinical and cognitive features typically follows a sequential course. However, in some cases, symptoms may be prolonged. To be defined as a concussion, the clinical signs and symptoms cannot be explained by drug, alcohol, or medication use, other injuries (such as cervical injuries, peripheral vestibular dysfunction), or other comorbidities (e.g., psychologic factors or coexisting medical conditions).

EPIDEMIOLOGY

According to the Centers for Disease Control and Prevention (CDC), as many as 3.8 million sport-related TBIs may occur in the United States annually with 70–90% of these injuries classified as concussion. One study suggested that current surveillance systems may capture only one out of every nine concussions.

Approximately 20% of middle and high school children report a lifetime prevalence of concussion. Sports participation is the most common mechanism of injury. An estimated 1.1–1.9 million recreational and sports-related concussions occur each year in children 18 years or younger. In gender-comparable sports, female athletes report higher rates of concussion than males, and both groups are more likely to suffer a concussion in competition than at practice. Among males, the incidence of concussion is highest in collision (contact) sports, including rugby, American football, ice hockey, lacrosse, basketball, soccer, and wrestling. Among females, the incidence of concussion is highest

in soccer, lacrosse, and field hockey. Other sports and recreational activities in which concussions frequently occur include bicycling, skateboarding, skiing, and snowboarding. Younger children may have playground-associated concussions.

PATOPHYSIOLOGY

The constellation of symptoms associated with concussion are not caused by observable structural injury or hemorrhage; clinical imaging studies (MRI/CT) typically are normal. However, there is a proposed cascade of events that lead to the clinical syndrome. A sudden acceleration, deceleration, or rotation of the brain is thought to result in parenchymal shear stress and strain that disrupts neuronal function in a cascade of ionic and metabolic fluctuations. Affected neurons experience massive depolarization and then require additional adenosine triphosphate (ATP) to restore cellular homeostasis. Glucose levels dramatically increase to fuel ATP production, which ultimately causes lactic acid accumulation. At the same time this process occurs, there is a decrease in cerebral blood flow, which may persist for several weeks. Consequently, less glucose is available when it is most needed to fuel ATP for ionic recovery. The signs and symptoms of concussion are thought to reflect the energy crisis or mismatch between the demand and availability of fuel in the brain after trauma.

SIGNS AND SYMPTOMS

Signs and symptoms of concussion can be classified into five categories, including somatic, vestibular, cognitive, emotional, and sleep related (Table 729.1). Acutely, headache is the most commonly reported symptom, followed by dizziness, difficulty concentrating, and confusion. Sleep disturbance, anxiety, and mood-related symptoms are more likely to occur several weeks post-injury. Brief loss of consciousness occurs in less than 5% of SRCs and is not associated with injury severity or time to recover. The most reliable predictor of recovery is initial symptom burden; children who experience greater symptom load and severity are at increased risk of PPCS. However, several noninjury-related factors can also affect recovery, including female sex, history of migraines, history of prior concussion, poorer preinjury child adjustment, family dysfunction, neurodevelopmental disorder (e.g., learning disability, attention-deficit/hyperactivity disorder [ADHD]), and psychiatric illness (e.g., anxiety, depression).

Although concussion typically results in an immediate onset of short-lived neurologic dysfunction that resolves spontaneously, signs and symptoms may develop over several minutes to hours. The diagnosis can be challenging and further complicated by the presence of concussion-like symptoms in noninjured athletes. Children with preexisting neurodevelopmental disorders, mental health concerns, history of prior concussion, or headaches/migraines may endorse concussion-like symptoms in the absence of injury. A reasonable mechanism of injury needs to be identified as well as a measurable change from baseline symptoms. To this end, age-appropriate symptom scales or checklists may be useful in assessing SRC and monitoring recovery (Table 729.1). Many symptom rating scales are available, and some are incorporated into sideline assessment tools, including the Sport Concussion Assessment Tool version 6 (SCAT6), which is approved for age 13 years and older. It is important to use a developmentally appropriate scale for younger children (e.g., Child-SCAT6 for children age 5–12 years) and to use the same tool in subsequent assessments to allow for tracking of symptoms over time.

INITIAL ASSESSMENT AND TOOLS

The initial diagnosis and management of concussion often begins on the field, rink, or court. Whether on the sideline and/or at a medical clinic, the first step is to rule out an injury that requires immediate attention. Acute care should include cervical spine stabilization, evaluation of airway, breathing, and circulation, and motor and sensory neurologic testing. Once a spinal cord injury or more severe injury to the brain is ruled out, it is important to: (1) perform a detailed evaluation of the athlete's mental status, (2) assess signs and symptoms, and (3) identify risks for delayed recovery (i.e., neurodevelopmental disorders, mental health concerns, history of prior concussion, or headaches/migraines). This process is facilitated by use of a validated sideline

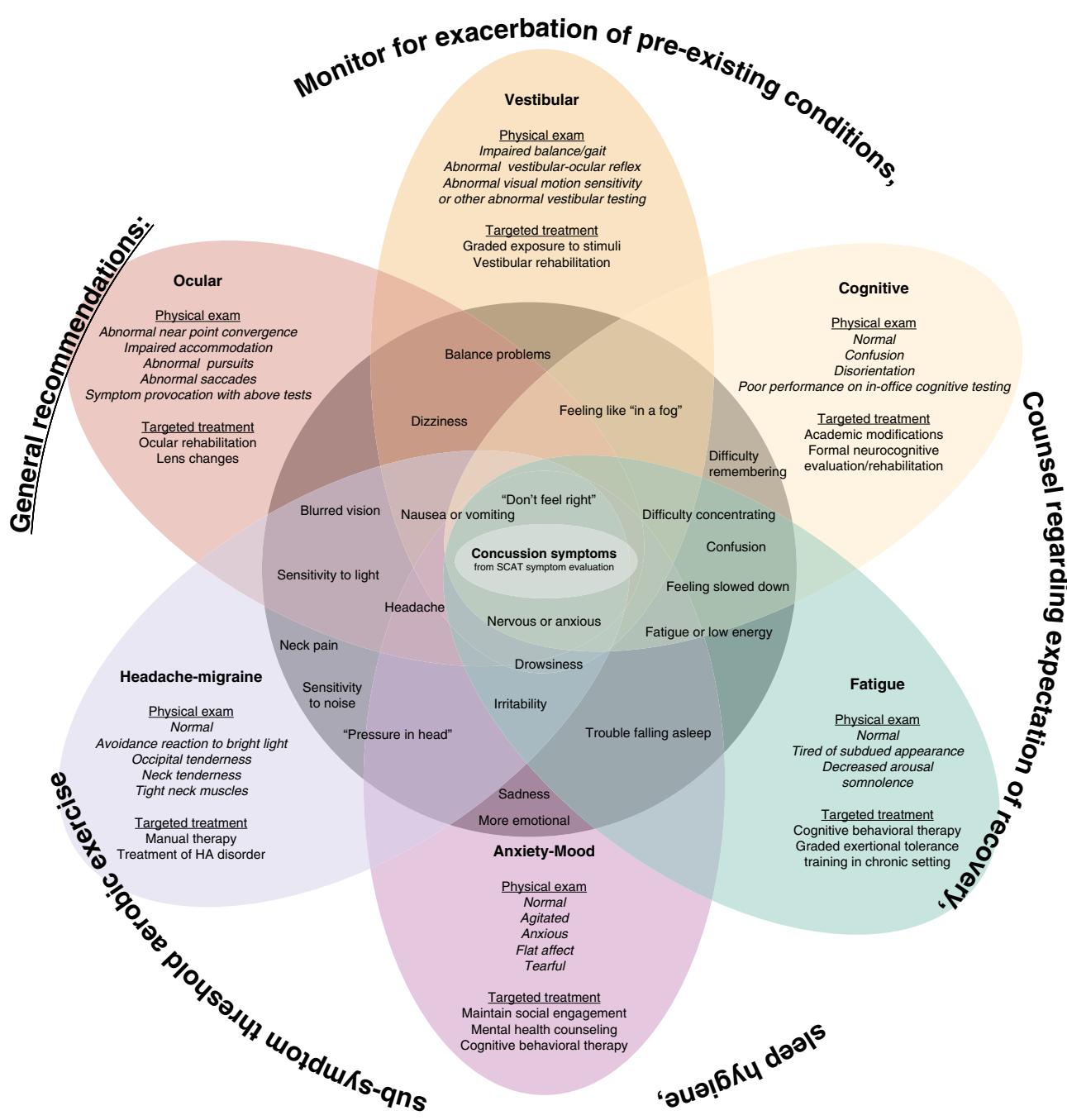


Fig. 729.1 Constellation of symptoms after concussion. Overlapping clinical domains to monitor and facilitate individualized management after concussion. (From Harmon KG, Clugston JR, Dec K, et al. American Medical Society for Sports Medicine position statement on concussion in sport. Br J Sports Med. 2019;53[4]:213–225.)

assessment tool. SCAT6 is recommended and includes standardized methods for recording relevant demographics, observable signs of injury, postconcussion symptoms, and memory function (excluding children <12 years), as well as the GCS, cervical spine assessment, brief neurologic exam, and the modified Balance Error Scoring System (m-BESS). Another often-used sideline assessment is the Sideline Assessment of Concussion, which includes a mental status exam, brief neurologic exam, and cognitive screen.

The Balance Error Scoring System (BESS) measures postural stability or balance and consists of six stances, three on a firm surface and the same three stances on an unstable (medium density foam) surface. The modified BESS (m-BESS) is frequently used because it does not rely on availability of medium-density foam for administration. Both include three stances: feet shoulder width apart, a tandem stance (one foot in

front of the other), and a single-leg stance on the person's nondominant leg, which are performed for 20 seconds with eyes closed and hands on the iliac crests. An error is recorded each time athletes lift their hands off their hips, open their eyes, step, stumble, fall, remain out of the test position for more than 5 seconds, move hips into more than 30 degrees of flexion or abduction, or lift their forefoot or heel. Normative data are available for comparison, although preseason balance screening provides more precise, individualized data. Furthermore, most evidence suggests that balance impairments generally resolve within 3 days postinjury.

Clinicians should screen for vision problems after concussion. In addition to visual acuity and visual field testing, the Vestibular Ocular Motor Screening Assessment (VOMS) is another tool that is increasingly used to evaluate concussion. It involves a standardized method to

Table 729.1 Postconcussion Symptom Scale

	NONE	MILD	MODERATE	SEVERE
Headache	0	1 2	3 4	5 6
"Pressure in head"	0	1 2	3 4	5 6
Neck pain	0	1 2	3 4	5 6
Nausea or vomiting	0	1 2	3 4	5 6
Dizziness	0	1 2	3 4	5 6
Blurred vision	0	1 2	3 4	5 6
Balance problems	0	1 2	3 4	5 6
Sensitivity to light	0	1 2	3 4	5 6
Sensitivity to noise	0	1 2	3 4	5 6
Feeling slowed down	0	1 2	3 4	5 6
Feeling like "in a fog"	0	1 2	3 4	5 6
"Don't feel right"	0	1 2	3 4	5 6
Difficulty concentrating	0	1 2	3 4	5 6
Difficulty remembering	0	1 2	3 4	5 6
Fatigue or low energy	0	1 2	3 4	5 6
Confusion	0	1 2	3 4	5 6
Drowsiness	0	1 2	3 4	5 6
More emotional	0	1 2	3 4	5 6
Irritability	0	1 2	3 4	5 6
Sadness	0	1 2	3 4	5 6
Nervous or anxious	0	1 2	3 4	5 6
Trouble falling asleep	0	1 2	3 4	5 6

From Echemendia RJ, Meeuwisse W, McCrory P, et al. Sport concussion assessment tool—5th edition. *Br J Sports Med.* 2017;51:851–858.

assess smooth pursuits, horizontal and vertical saccades, convergence, horizontal vestibular ocular reflex, and visual motion sensitivity. Findings on the VOMS have been shown to distinguish children with concussion from uninjured controls, and vestibular-ocular dysfunction may have a particularly deleterious effect on academics.

Neuropsychologic assessment quantifies cognitive symptoms of concussion and can help to identify comorbidities that can complicate the diagnosis. The areas identified as most vulnerable to injury include attention and executive function (e.g., speed of processing), new learning and memory, and reaction time. Obtaining preseason or "baseline" data enables clinicians to accurately detect cognitive impairment after injury and aids interpretation of data for athletes with preexisting or contextual factors that affect cognitive function (e.g., neurodevelopmental disorder, sleep, anxiety, and depression). Computer-administered neurocognitive tests are frequently used because the cost and availability of trained neuropsychologists to administer and interpret more comprehensive tests are prohibitive. Further, testing may be of additional benefit in determining appropriate school and home interventions for children who go on to experience PPCS.

The application of neuropsychologic assessment varies depending on the time of referral. Research generally supports the use of brief cognitive screens acutely (~3 days postinjury) such as those incorporated

into the SCAT and SAC. Computerized administered neurocognitive assessment or a hybrid approach that includes paper and pencil measures of function are most often administered subacutely (~4–30 days postinjury) to assist in return-to-play decision-making, documenting lingering cognitive deficits, and providing rationale for academic supports or accommodations. The purpose of neuropsychologic assessment for patients with prolonged or chronic postconcussion symptoms (30+ days) is to provide the referring clinician and patient with additional insight into injury and noninjury factors affecting recovery, as well as their impact on cognitive function. Symptoms of comorbidities, including sleep deprivation, deconditioning, and pain, closely resemble postconcussion symptoms and similarly influence health-related status and cognition. Research also indicates that anxiety and depression, family functioning, and caregiver adjustment, as well as neurodevelopmental disorders (e.g., learning disability or ADHD) are strong predictors of prolonged symptoms.

In addition to ruling out more severe injury, the primary goal of both sideline assessment and/or office-based assessment is to prevent concussed athletes from returning to play prematurely. The brain is likely more vulnerable to reinjury immediately after concussion and until ionic and metabolic functioning normalizes. Consistent with this, most reinjuries occur within the first 10 days of an initial concussion. Thus, if a concussion is suspected, it is often wise to remove younger athletes from play for 24 hours or until the diagnosis of concussion can be confidently ruled out. Athletes who experience prolonged loss of consciousness, focal neurologic deficits, excessive somnolence, progressively worsening headache pain, repeated vomiting, slurred speech, and significant confusion may need to be seen in the emergency department where brain imaging can be conducted to rule out more severe head injury.

A blood test (Brain Trauma Indicator) is FDA approved for patients ≥18 years of age with concussion who have normal mental status) to help identify patients in need of cranial imaging. The test measures brain proteins, glial fibrillary acid protein, and ubiquitin C-terminal hydrolase-1, and may also be useful in detecting concussion in children.

MANAGEMENT

After diagnosis and removal from play, the initial management strategy is education of the child and parents about concussion, including the signs and symptoms, effects on cognition, and expected trajectory of recovery. Early limited, subsymptom levels of physical activity may improve recovery, whereas complete rest beyond 2–3 days is associated with delayed recovery. Children (symptomatic or asymptomatic) who can tolerate light exercise soon after injury should be encouraged to do so because it prevents deconditioning and can help with sleep and mood regulation. Importantly, early moderate and intense exercise is associated with symptom exacerbation and longer recovery times, and exercise of any intensity is deferred if it provokes symptoms in the first few days postinjury. Most children will begin to achieve some level of activity tolerance within 2–3 days. Management plans should then focus on gradually and progressively resuming noncontact, low-risk physical activity until full recovery (*Table 729.2*).

Most children who sustain a concussion will experience full recovery with adherence to relative rest, followed by graduated return to physical and cognitive activity. Nonetheless, some athletes require targeted symptom management, particularly when they are slow to improve (*Table 729.3*; see *Fig. 729.1*). Acetaminophen or NSAIDs may help to reduce acute headache pain. Prescription medications are sometimes warranted, including topiramate, amitriptyline, or cyproheptadine for posttraumatic headaches, peripheral nerve blocks for occipital or cervicogenic headaches, and gabapentin for headaches with a neuropathic component. Otolaryngology referral or vestibular therapy is recommended for management of dizziness, vertigo, and imbalance. For children with visual disturbance, assessment and visual rehabilitation therapy managed by an optometrist or ophthalmologist is appropriate. Psychologic assessment and intervention, particularly cognitive behavioral therapy, is recommended

Table 729.2 Graduated Return to Play Protocol

STAGE	AIM	ACTIVITY	GOAL OF EACH STEP
1	Symptom-limited activity	Daily activities that do not provoke symptoms	Gradual reintroduction of work/school activities
2	Light aerobic exercise	Walking or stationary cycling at slow to medium pace. No resistance training	Increase heart rate
3	Sport-specific exercise	Running or skating drills. No head impact activities	Add movement
4	Noncontact training drills	Harder training drills (e.g., passing drills). May start progressive resistance training	Exercise, coordination, and increased thinking
5	Full contact practice	After medical clearance, participate in normal training activities	Restore confidence and assess functional skills by coaching staff
6	Return to sport	Normal game play	

NOTE: An initial period of 24–48 hr of both relative physical rest and cognitive rest is recommended before beginning the return to sport progression.

There should be at least 24 hr (or longer) for each step of the progression. If any symptoms worsen during exercise, the athlete should go back to the previous step. Resistance training should be added only in the later stages (stage 3 or 4 at the earliest). If symptoms are persistent (e.g., more than 10–14 days in adults or more than 1 mo in children), the athlete should be referred to a healthcare professional who is an expert in the management of concussion.

From Patricios JS, Schneider KJ, Dvorak J, et al. Consensus statement on concussion in sport: the 6th International Conference on Concussion in Sport—Amsterdam, Oct 2022. *Br J Sports Med*. 2023;57:695.

Table 729.3 Common Potential Interventions for Specific Symptoms After Pediatric Concussion

SPECIFIC SYMPTOMS	POTENTIAL INTERVENTIONS
Headache	Lifestyle modifications (water intake, meal schedule, sleep, and exercise), cervicovestibular therapy, acute medications, preventive medications, and avoiding overuse of acute medications
Light-Headedness or Exercise Intolerance	Increase water and salt intake and gradual increase in exercise
Dizziness or Neck Pain	Vestibular therapy and cervical spine therapy
Balance or Coordination Difficulties	Neuromuscular training
Sleep Difficulties	Lifestyle modifications (bedtime routine, white noise, avoid caffeine, and exercise earlier), and melatonin
Anxiety or Mood Problems	Counselling, antidepressants, and anxiolytics
Cognitive Difficulties	Cognitive testing and academic accommodations

From Beauchamp MH, Degeilh F, Rose SC. Improving outcome after paediatric concussion: challenges and possibilities. *Lancet Child Adolesc* 2023;7:728–738 (Panel 2, p. 733).

for athletes who experience worsening or newly developed symptoms of anxiety or depression. Both are potentially heightened as a direct consequence of concussion as well as the resulting limitations on everyday activities and social interaction. A multidisciplinary and collaborative approach to target specific treatments is advised for children whose symptoms do not show improvement with standard behavioral interventions.

Return to School

Of particular importance to children and their families is the effect of concussion on cognitive function and school performance.

Children and adolescents exposed to greater levels of cognitive stress endorse worse symptoms and experience longer recovery after concussion. Students who experience postconcussion symptoms report difficulty in school. There is also evidence that overly restricting cognitive exertion and school participation can delay recovery. Current recommendations focus on using self-reported symptoms to determine school readiness, followed by increasing exposure to classroom learning, tests, and assignments (Table 729.3). In general, children and adolescents are encouraged to attend school, even if on a modified schedule, in 2–3 days or sooner, with a program of academic adjustments and modifications that allow for ongoing learning to occur with minimal symptom provocation. Clinicians should provide documentation to schoolteachers and administrators requesting compressed assignments, more time to complete tests or assignments, deferred examinations, rest breaks, audiobooks, oral teaching, large font printed material, or preprinted notes where indicated.

Return to Play

There is a six-stage return-to-play (RTP) protocol for a safe return to activities (see Table 729.2). Starting with physical rest, athletes are progressed to light aerobic exercise, moderate levels of sport-specific exercise, noncontact training drills, full contact practice, and normal game play. Athletes should be completely asymptomatic, free of medications used to treat concussion symptoms, at full school, and back to baseline functioning on all domains tested before the injury before returning to contact or collision sports. Children and adolescents should remain at each stage of rehabilitation for no less than 24 hours before advancing to the next level. Thus a minimum of 5 days should pass before consideration of full return to competition. If symptoms return at any stage of exertion, the athlete should rest until the symptoms resolve and then return to the previous level of exertion. The final decision for RTP should be made by a licensed clinical provider with experience in the evaluation and management of sports-related concussions. Note that some states or schools require an extended minimum number of symptom-free days before RTP, so clinicians need to be aware of the laws or local recommendations regarding RTP.

Risks for Persistent Postconcussion Symptoms

From 80–90% of children and adolescents diagnosed with concussion will clinically recover within 4 weeks. Factors associated with prolonged recovery include a history of prior concussions, female

Table 729.4 Graduated Return to School Strategy

STAGE	AIM	ACTIVITY	GOAL OF EACH STEP
1	Daily activities at home that do not give the child symptoms	Typical activities of the child during the day as long as they do not increase symptoms (e.g., reading, texting, screen time). Start with 5-15 min at a time and gradually build up	Gradual return to typical activities
2	School activities	Homework, reading, or other cognitive activities outside of the classroom	Increase tolerance to cognitive work
3	Return to school part-time	Gradual introduction of schoolwork. May need to start with a partial school day or with increased breaks during the day	Increase academic activities
4	Return to school full time	Gradually progress school activities until a full day can be tolerated	Return to full academic activities and catch up on missed work

From Patricios JS, Schneider KJ, Dvorak J, et al. Consensus statement on concussion in sport: the 6th International Conference on Concussion in Sport–Amsterdam, Oct 2022. *Br J Sports Med*. 2023;57:695.

sex, history of migraines, neurodevelopmental disorder (e.g., ADHD, learning disability), successive concussion soon after recovery, and acute symptom severity and burden. Female sex and initial symptom severity are the factors associated with more persistent symptoms in adolescents.

Retiring Young Athletes

Retirement from contact sports is rare but sometimes indicated, even in younger athletes. Indications for retirement include chronic neuropsychologic deficit, increased recovery times for successive injuries, decreased threshold for repeat concussions, and multiple concussions over the course of an athletic career.

COMPLICATIONS/LONG-TERM EFFECTS

Second impact syndrome, seen more frequently in younger athletes than adults, refers to a rare, catastrophic neurologic injury involving diffuse cerebral swelling that purportedly occurs in athletes who sustain a second head injury before full recovery from a concussion. Although second impact syndrome is rare, its occurrence highlights the importance of removing children with concussion from play and other activities that place them at increased risk of head injury until fully recovered. Pathogenic variants in *CACNA1A* have been associated with delayed and severe cerebral edema after minor head trauma.

Some literature suggests that young athletes who suffer repetitive head impacts and multiple concussions may be at risk for neurodegenerative diseases, such as chronic traumatic encephalopathy (CTE) or Alzheimer disease. CTE describes pathologic changes in the brain observed postmortem, which are hypothesized to be associated with changes in mood, behavior, and cognition function. At present, there is no way to diagnose CTE in living persons and its incidence and prevalence are unknown.

PREVENTION

The strongest evidence for concussion prevention is in support of concussion education initiatives, age limits on contact, fair play, and adherence to rules of the game or competition. Additionally, there is some evidence that neck strengthening may reduce the risk of concussion. Current research shows no proven benefit to personal protective equipment (i.e., helmets, mouthguards) or dietary supplements in reducing the risk of concussion or its severity, although it is important for athletes to wear properly fitted sport specific protective equipment to prevent *more serious* head injury and maxillofacial and dental trauma.

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Chapter 730

Cervical Spine Injuries

Julie M. Kerr and Joseph A. Congeni

Sports participation has surpassed motor vehicle crashes as the number one cause of cervical spine injuries (primarily involving soft tissue) in youth older than 8 years of age. American football, hockey, wrestling, and gymnastics have the highest incidence in the United States; internationally, rugby is nearly as high. Catastrophic cervical spine injuries fortunately are rare but can occur as a result of the scrum or tackling in rugby and tackling plays in American football.

The normal cervical spine has a lordotic curve, allowing it to absorb shock and dissipate force with application of an axial force. When the neck is flexed forward, the spine straightens, losing this shock-absorbing property. An axial load to the top of the head in this flexed position transmits force through the spine.

SOFT TISSUE INJURY

The most frequent injury resulting from trauma to the head and neck involves the muscles, tendons, and ligamentous structures. Even though strains, sprains, and contusions are common and are managed with cervical, scapulothoracic, and shoulder-strengthening exercises, thorough evaluation is required to rule out more serious injuries. Even without bony abnormalities, the cervical spine may become unstable secondary to soft tissue injury.

Spinal laxity results when most restraining ligaments are injured. When compared with adjacent vertebra, laxity should horizontally be less than 3.5 mm and angular displacement less than 11 degrees on plain flexion/extension films. However, younger athletes have more baseline laxity, making the criteria less applicable, and muscle spasm can acutely mask instability. If subluxation is remotely suspected, a hard cervical collar should be placed and flexion/extension views obtained again at 2–4 weeks when inflammation and spasm have subsided. A loss of lordosis on lateral x-ray is associated with significant weakness of cervical muscles, particularly the cervical extensors. Disk injuries are rare in pediatric patients. Rupture or herniation must be considered in any cervical pain differential (see Chapter 81).

SPEAR TACKLER'S SPINE

This clinical entity is characterized by progressive spinal changes secondary to incorrect tackling form. Findings on plain x-ray consist of (1) narrowing of cervical spinal canal, (2) loss or reversal of normal cervical lordosis, and (3) preexisting minor posttraumatic x-ray evidence of bony

or ligamentous injury. Although rule changes in collision and contact sports have limited the practice of contacting an opponent with a “head-down” neck position, this condition persists. Most experts argue that this condition disqualifies athletes from return to play.

CERVICAL FRACTURES

All significant neck injuries should be treated seriously until cleared with appropriate examination and imaging. Although many cervical fractures are stable, improper management or inadequate evaluation could produce catastrophic results. *Until formally evaluated, the patient should be immobilized and treated as if the patient has an unstable cervical fracture* (see Chapter 81).

STINGERS (BURNERS)

Stingers are unilateral (*never bilateral*) peripheral nerve injuries occurring at an anatomic location between the cervical nerve root and the brachial plexus. Three proposed mechanisms include traction or tensile stretch injury, compressive injury, and direct trauma. A typical presentation is a transient episode of unilateral burning pain, with or without numbness, that radiates from the shoulder, down the upper arm, and into the hand. Symptoms of C5 and C6 root injury with deltoid and biceps weakness are the most common presentation. These symptoms may last for several minutes to days but do not result in permanent neurologic deficit or abnormal imaging evaluations. Examination should assess for weakness, especially shoulder abduction, external rotation, and elbow flexion. The cervical spine should have full and pain-free range of motion and no tenderness to palpation.

The Spurling Compression test helps to assess for cervical radiculopathy as a cause of upper extremity pain. The patient is seated with their neck tilted to the affected side. In a positive test, the pain is reproduced with gentle axial compression. The test has high specificity (~93%) but relatively low sensitivity (~30%), meaning that positive tests indicate likely cervical radiculopathy but many patients with cervical radiculopathy will not have a positive test.

Return to play may be considered the same day if the exam is reassuring. This requires complete resolution of symptoms, full range of motion, and normal strength. Multiple stingers, bilateral symptoms, or symptoms persisting for longer than one hour should prompt further evaluation with cervical spine radiographs and other imaging modalities as indicated before resumption of any physical activities.

BURNING HANDS SYNDROME

The athlete with this syndrome presents with intense paresthesia and associated hand and arm weakness in both upper extremities. This is suggestive of a central cord syndrome with cord compression of the spinothalamic and corticospinal tracts. As with stingers, most of these episodes resolve in minutes to days. Persistent symptoms or repeated episodes warrant further evaluation and imaging.

TRANSIENT QUADRIPIARESIS

Transient quadripareisis is a temporary neurologic episode encompassing sensory symptoms with or without motor changes. Transient quadripareisis is also known as *cervical cord neurapraxia*, *commotio spinalis*, and *spinal cord concussion*. Transient quadripareisis can be divided into three types: plegia (complete loss of motor function), paresis (motor weakness), and paresthesia (sensory symptoms only). There is also a three-part grading system: grade 1 symptoms lasting less than 15 minutes, grade 2 symptoms lasting 15 minutes to 24 hours, and grade 3 symptoms persisting beyond 24 hours. Transient quadripareisis must be differentiated from a stinger, and the player should be removed from activity and spinal cord injury considered.

Mechanisms of injury include hyperextension, hyperflexion, and axial loading. Anatomically, when the neck is hyperflexed or hyperextended, the spinal canal is narrowed by up to 30%, increasing the likelihood of cord injury.

Evaluation should start with plain flexion and extension films if stable. CT should be used if cervical fracture is suspected. MRI should then be used to evaluate for intrinsic spinal cord abnormalities or ongoing cord or root compression.

Table 730.1 Return to Play

NO CONTRAINDICATION TO RTP	
Healed fractures	Healed C1 or C2 fracture with normal cervical spine ROM Healed subaxial fracture without sagittal plane deformity Asymptomatic clay-shoveler's (C7) spinous process avulsion fracture
Congenital conditions	Klippel-Feil (single-level anomaly not C0/C1 articulation) Spina bifida occulta
Degenerative/ postsurgical conditions	Cervical disk disease (no change in baseline neurologic status) Single-level ACF with/without instrumentation Single- or multiple-level posterior cervical laminotomy
Recurrent stingers	Fewer than three episodes lasting <24 hours Must have full cervical range of motion No persisting neurologic deficit
Transient quadripareisis	Single episode Full cervical range of motion Normal neurologic exam No radiologic instability Normal spinal reserve (as evidenced on MRI)
RELATIVE CONTRAINDICATION TO RTP	
Stingers/burners	Prolonged symptomatic burner/stinger Three or more stingers
Transient quadripareisis	Transient quadripareisis lasting >24 hours More than 1 episode with symptoms of any duration
Postsurgical	Healed two-level ACF PCF with/without instrumentation
ABSOLUTE CONTRAINDICATION TO RTP	
Transient quadripareisis and any one or more of	Cervical myelopathy Continued neck discomfort Reduced ROM Neurologic deficit from baseline after injury
Surgical procedures	C1 + C2 fusion Cervical laminectomy Three-level ACF or PCF
Soft tissue injuries	Asymptomatic ligamentous laxity (>11 degrees of kyphotic deformity) C1 + C2 hypermobility with anterior dens >3.5 mm (adult), >4 mm (child), i.e., Down syndrome Symptomatic cervical disk herniation
Other conditions	Spear tackler's spine Multilevel Klippel-Feil anomaly (see Chapter 721.2) Healed subaxial fracture with sagittal kyphosis, coronal plane abnormality, or cord encroachment Ankylosing spondylitis Rheumatoid arthritis with spinal abnormalities Spinal cord abnormality (cord edema, compression, etc.) Arnold-Chiari syndrome Basilar invagination Occipital-C1 assimilation (occipitalization or connection) Spinal stenosis (canal width <13 mm between C3 and C7)

ACF, Anterior cervical fusion; PCF, posterior cervical fusion; ROM, range of motion; RTP, return to play.

Adapted from Cantu R, Li YM, Abdulhamid M, et al. Return to play after cervical spine injury in sports. *Curr Sports Med Rep*. 2013;12:14–17.



Fig. 730.1 An MRI (sagittal) demonstrating spinal cord contusion (edema in central portion of spinal cord). (From Krabak BJ, Kanarek SL. Cervical spine pain in the competitive athlete. *Phys Med Rehabil Clin N Am.* 2011;22:459–471. Fig. 2).

Return to play for transient quadriplegia is heavily debated and lacks data to guide decision-making. Some experts argue that one episode is a contraindication to return to contact sports, whereas others agree with using the Return to Play Table (Table 730.1) for absolute and relative contraindications for return. If allowed to return to play and a second episode of transient quadriplegia occurs, the complete workup must be repeated.

CONGENITAL SPINAL STENOSIS

Developmental narrowing of the cervical spinal canal predisposes an athlete to higher risk of spinal cord injury. This condition can be found incidentally while working up other conditions. Currently, the “gold standard” imaging modality is an MRI measuring a canal width of <13 mm between C3 and C7 to define stenosis, with “normal” being greater than 15 mm.

Functional stenosis can be seen with dynamic MRI in flexion and extension to determine whether the canal space decreases with movement. The positioning of the canal in flexion or extension causes narrowing from movement of the vertebra and ligament, respectively. The measured diameter may be irrelevant if disk protrusion or ligament hypertrophy causes compression. This narrow “reserve space” around the spinal cord puts the athlete at greater risk for injury as compared with the same force applied to a normal spine.

SPINAL CORD INJURY

Spinal cord injury is the most devastating complication of cervical trauma. Hemorrhage and transection are considered irreversible and associated with complete cord injury, whereas contusion and edema are considered to have more potential for recovery (Fig. 730.1). These severe injuries should be managed by providers with expertise in this area.

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Chapter 731

Heat Injuries

Gregory L. Landry and Andrew M. Watson

Heat illness is among the leading causes of death in U.S. high school athletes. It is a continuum of clinical signs and symptoms that can be mild (heat stress) to fatal (heat stroke). Children are more vulnerable to heat illness than adults because they have a greater ratio of surface area to body mass and produce greater heat per kilogram of body weight during activity. The sweat rate is lower in children, and the temperature at which sweating occurs is higher. Although there is considerable interindividual variability, children can take longer to acclimatize to warmer, more humid environments (typically 8–12 near-consecutive days of 30- to 45-minute exposures). Children also have a blunted thirst response compared with adults and might not consume enough fluid during exercise in hot, humid environments to prevent dehydration. In addition, certain medications may predispose to heat-related injury (Table 731.1).

Three major categories for heat illness are generally used: heat cramps, heat exhaustion, and heat stroke (Table 731.2). However, symptoms of heat illness overlap and progress as the core temperature rises. **Heat cramps** are the most common heat injury and usually occur in mild dehydration and/or salt depletion, typically affecting the calf and hamstring muscles. They tend to occur later in activity, as muscle fatigue is reached and water loss and sodium loss worsen. Heat cramps will normally respond to oral rehydration with electrolyte solution and with gentle stretching. The athlete can return to play when the ability to perform is not impaired. Other minor heat illnesses include heat syncope, heat edema, and heat tetany. **Heat syncope** is fainting after prolonged exercise, attributed to poor vasomotor tone and depleted intravascular volume; it responds to fluids, cooling, and supine positioning. **Heat edema** is mild edema of the hands and feet during initial exposure to heat; it resolves with acclimatization. **Heat tetany** is carpopedal tingling or spasms caused by heat-related hyperventilation during short periods of exposure to intense heat. It responds to moving to a cooler environment and decreasing respiratory rate (or rebreathing by breathing into a bag).

Heat exhaustion is a moderate illness with a core temperature of 37.7–40°C (100–104°F). It is manifested as weakness, fatigue, headache, nausea, vomiting, dizziness, orthostasis, piloerection, and possibly syncope. Central nervous system dysfunction is mild, if present. Treatment includes moving to a cool environment, cooling the body with fans, removing excess clothing, and placing ice over the groin and axillae. If a patient is not able to tolerate oral rehydration, IV fluids are indicated. Patients should be monitored, including rectal temperature, for signs of heat stroke. If rapid improvement is not achieved, transport to an emergency facility is recommended.

Heat stroke is a severe illness manifested by central nervous system disturbances and potential tissue damage. It is a medical emergency; the mortality rate is up to 50%. Sports-related heat stroke is characterized by profuse sweating and is related to intense exertion, whereas “classic” heatstroke with dry, hot skin is of slower onset (days) in elderly or chronically ill persons. Rectal temperature is usually >40°C (104°F). Significant damage to the heart, brain, liver, kidneys, and muscle occurs, with possible fatal consequences if untreated. Treatment is immediate whole-body cooling via cold water immersion (Table 731.3). Airway, breathing, circulation, core temperature, and central nervous system status should be monitored constantly. Rapid cooling should be ceased when core temperature is approximately 38.3–38.9°C (101–102°F). IV fluid at a rate of 800 mL/m² in the first hour with normal saline or lactated Ringer solution improves

Table 731.1 Medications and Drugs That May Increase the Risk of Heat-Related Injury**MEDICATIONS**

Anticholinergic agents (including antihistamines)
 β Blockers
 Antipsychotics (including SSRIs, TCAs)
 Lithium
 Diuretics
 Salicylates
 Sympathomimetic agents
 Calcium channel blockers
 Antiseizure medications (topiramate, zonisamide)

DRUGS OF MISUSE/SUPPLEMENTS

Amphetamines (including ephedra)
 Cocaine
 Ecstasy
 Phencyclidine
 Cathinone (synthetic marijuana) agents
 LSD
 Alcohol
 Anabolic steroids

SSRI, selective serotonin reuptake inhibitors; LSD, lysergic acid diethylamide; TCA, tricyclic antidepressants.

Table 731.2 Spectrum of Heat Illness**HEAT CRAMPS AND DEHYDRATION: CAUTIOUS RETURN TO PLAY**

Muscle cramps
 Thirst
 Fatigue
 Light-headedness
 Sweating
 Flushed face

HEAT EXHAUSTION: REMOVE FROM PLAY

Dizziness
 Rapid pulse
 Headaches
 Nausea
 Vomiting
 Loss of coordination
 Profuse sweating
 Core temperature less than 40°C (104°F)

HEAT STROKE: MEDICAL EMERGENCY, CALL 911

Core temperature of 40°C (104°F) or higher
 Hot dry skin
 Multiple system failure
 Delirium
 Convulsions
 Abnormal vital signs

From Merkel DL, Molony JT Jr. Medical sports injuries in the youth athlete: emergency management. *Int J Sports Phys Ther*. 2012;7:242–251. Table 4.

intravascular volume and the body's ability to dissipate heat. Immediate transport to an emergency facility is necessary. Physician clearance is required before return to exercise.

Dehydration is common to all heat illness; consequently, measures to prevent dehydration may also prevent heat illness. Thirst is usually an adequate indicator of hydration status; excessive hypotonic fluid replacement beyond sweat and urine losses can lead to hyponatremia. Endurance athletes should be cautioned not to drink beyond thirst. Mild dehydration (2–3%) does not usually affect performance and itself does not cause cramping, fatigue, or heat stroke.

Exercise-associated hyponatremia ($\text{Na} < 135 \text{ mmol/L}$) may be asymptomatic or symptomatic (lightheadedness, nausea, headache, confusion, cerebral edema) and is often seen in endurance sports (marathon,

Table 731.3 Current Therapy for Heat-Related Illness

- Acclimatization is key for prevention of exertional heat illness.
- Heat illness is most effectively managed by immediate recognition of the signs and symptoms and proper diagnosis.
- Core body temperature measurement must be done with a rectal thermometer.

EXERCISE-ASSOCIATED COLLAPSE

- Continue walking after race to prevent development.
- Position the patient in the supine or Trendelenburg position and start fluid administration.

HEAT EXHAUSTION

- Provide rapid cooling with ice bags to areas adjacent to large vasculature (groin, neck, axilla).
- Administer oral or intravenous (IV) fluid to correct for hydration deficit.

HEAT STROKE

- Ensure the ability to maintain adequate circulation, airway, and breathing.
- Ice-water immersion is the most effective way to provide rapid cooling.*
- The goal of cooling is to reduce and maintain a temperature below 38.3°C (101°F).
- Transport to the hospital may be required if the patient's temperature is not reduced effectively or the patient does not return to normal mental status after 30 minutes of medical treatment.

From Cleland P. Heat illness. In: Kellerman RD, Rakel DP, Heidelbaugh JJ, Lee EM, eds. *Conn's Current Therapy 2023*. Philadelphia: Elsevier, 2023: p. 1390.

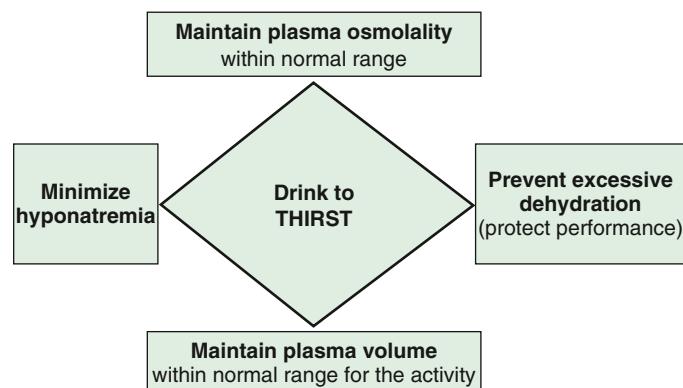


Fig. 731.1 Primary recommended fluid intake strategy to prevent symptomatic exercise-associated hyponatremia. (From Hew-Butler T, Rosner MH, Fowkes-Godek S, et al. Statement of the third international exercise-associated hyponatremia consensus development conference, Carlsbad, California, 2015. *Clin J Sport Med*. 2015;25:303–320. Fig. 1.)

triathlon, cycling, swimming), hiking, football, and police or military drills. Major risk factors include overdrinking water or hypotonic sports drinks, weight gain during exercise, exercise duration >4 hours, readily available fluids, and inexperienced or slow pace. Athletes are advised to be hydrated before exercise and should drink to thirst (Fig. 731.1). Fluids should contain sodium and not be ingested in excess.

During a football practice, for example, scheduled breaks every 20–30 minutes with helmets off can decrease the cumulative amount of heat exposure. Practices and competitions should be scheduled in the early morning or late afternoon to avoid the hottest part of the day. Guidelines have been published about modifying activity related to temperature and humidity (Fig. 731.2). Proper clothing such as shorts and T-shirts without helmets can improve heat dissipation. Prepractice and postpractice weight can be helpful in determining the amount of fluid necessary to replace (8 oz for each pound of weight loss). When practicing or performing in a warm environment, gradual acclimatization is recommended.

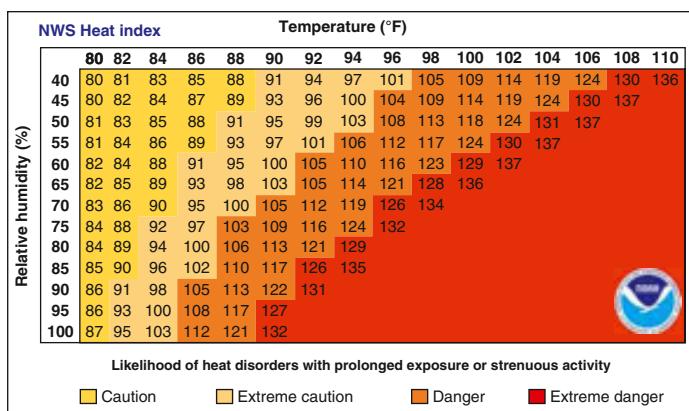


Fig. 731.2 Heat index. To determine the heat index using this chart, air temperature and the relative humidity need to be known. For example, if the air temperature is 100°F and the relative humidity is 55%, the heat index will be 124°F. When the relative humidity is low, the apparent temperature can actually be lower than the air temperature. (Courtesy National Weather Service, United States National Oceanic and Atmospheric Administration. <https://www.weather.gov/ama/heatindex>.)

Fluids with electrolytes and carbohydrates are important during exercise lasting longer than 1 hour. Salt supplements should not be used by most people because of the risk of causing hypernatremia and delayed gastric emptying. If excessive fluid intake contributes to hyponatremia, salt supplements will not avoid the decline in serum sodium. They may be useful in a person with a high sweat rate or recurrent heat cramps.

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Classification	Heat index	Effect on the body
Caution	80°F - 90°F	Fatigue possible with prolonged exposure and/or physical activity
Extreme danger	90°F - 103°F	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity
Danger	103°F - 124°F	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity
Extreme danger	125°F or higher	Heat stroke highly likely

Chapter 732

Nutrition and Endocrine Conditions in Athletes

Gregory L. Landry and Andrew M. Watson

Excessive physical training in young women can adversely affect reproductive function and bone mineral status, especially when combined with calorie restriction (Fig. 732.1; see Chapters 41 and 159).

The majority of bone mass is acquired by the end of the second decade of life (see Chapter 749). Approximately 60–70% of adult bone mass is genetically determined, and the remaining is influenced by three modifiable factors: exercise, calcium intake, and sex steroids (primarily estrogen). Exercise promotes bone mineralization in the majority of young women and should be encouraged. In females with eating disorders and those who exercise to the point of excessive weight loss with amenorrhea or oligomenorrhea, exercise can be detrimental to bone mineral acquisition, resulting in reduced bone mineral content, or osteopenia. In males, prolonged negative energy balance can similarly result in bone demineralization, although this may be more occult without the obvious sign of menstrual cycle disruption.

Specifically, bone mineralization is negatively affected by amenorrhea (absence of menstruation for 3 or more consecutive months). This may be influenced by abnormal eating patterns, or disordered eating, that results in insufficient caloric intake. When occurring together, disordered eating, amenorrhea, and osteoporosis represent the female athlete triad. A more inclusive definition refers to the interrelationships among energy availability, endocrine function, and bone mineral

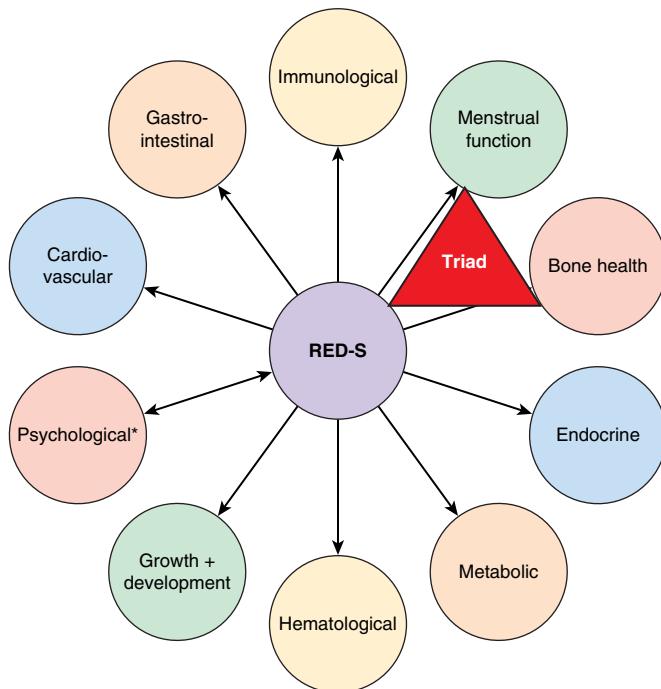


Fig. 732.1 Health consequences of relative energy deficiency in sport (RED-S) showing an expanded concept of the Female Athlete Triad to acknowledge a wider range of outcomes and the application to male athletes. *Psychologic consequences can either precede RED-S or be the result of RED-S. (Courtesy Dr. Naama W. Constantini, Shaare Zedek Medical Center, Hebrew University, Israel.)

density, as athletes are distributed along a spectrum of health and disease. The **male athlete triad** describes the impact of these interrelated problems in male athletes. In addition, the International Olympic Committee introduced the concept of **relative energy deficiency in sport** (RED-S), outlining the myriad physiologic, psychologic, and performance consequences of low energy availability in both male and female athletes (see Fig 732.1). At health supervision visits and the pre-participation physical examination, special attention should be given to screening for any unhealthy features of the female or male athlete triads (Tables 732.1 and 732.2).

In both male and female athletes, low energy availability can result in disruption of the hypothalamic-pituitary-gonadal axis. Menstrual abnormalities (including amenorrhea) result from

Table 732.1 Recommended Screening Questions for the Female Athlete Triad*

- Have you ever had a menstrual period?
- How old were you when you had your first menstrual period?
- When was your most recent menstrual period?
- How many periods have you had in the past 12 months?
- Are you presently taking any female hormones (estrogen, progesterone, birth control pills)?
- Do you worry about your weight?
- Are you trying to or has anyone recommended that you gain or lose weight?
- Are you on a special diet or do you avoid certain types of foods or food groups?
- Have you ever had an eating disorder?
- Have you ever had a stress fracture?
- Have you ever been told you have low bone density (osteopenia or osteoporosis)?

*The Triad Consensus Panel recommends asking these screening questions at the time of the sport preparticipation evaluation.

From Constantini NW. Medical concerns of the dancer. Book of Abstracts. XXVII FIMS World Congress of Sports Medicine, Budapest, Hungary, 2002. p. 151.

Table 732.2 Recommended Screening Questions for the Male Athlete Triad

- Do you worry about your weight?
- Are you trying or has anyone recommended that you lose or gain weight?
- Are you on a special diet, or do you avoid certain types of foods or food groups?
- Have you ever had an eating disorder?
- Have you ever had a stress fracture?
- Have you ever been told that you have low bone density or osteoporosis?
- Have you ever been diagnosed with low testosterone levels?
- Do you have low libido (sex drive)?
- Do you have morning erections?*
- Do you need to shave your facial hair less frequently?*

*Recommend inclusion on only preparticipation physical examinations for postpubertal athletes.

From Fredericson M, Kussman A, Misra M, et al. The male athlete triad – a consensus statement from the Female and Male Athlete Triad Coalition part II: diagnosis, treatment, and return-to-play. *Clin J Sport Med*. 2021;31(4):349–366. Box 1.

suppression of the spontaneous hypothalamic pulsatile secretion of gonadotropin-releasing hormone (Fig. 732.2; see Chapter 159.1). It is believed that the amenorrhea results from reduced energy availability, defined as energy intake minus expenditure. Energy availability below a threshold of 30 kcal/kg/day lean body mass is thought to result in menstrual disturbances, whereas availability at or above 45 kcal/kg/day is generally considered sufficient for optimal physiologic function. Other causes of menstrual cycle irregularities to be ruled out are pregnancy (see Chapter 161), pituitary tumors, thyroid abnormalities, polycystic ovary syndrome (see Chapter 589), anabolic-androgenic steroid use (see Chapters 157 and 733), and other medication side effects. Negative energy balance also appears to disrupt thyroid function and appetite-regulating hormones (e.g., leptin, ghrelin), increase resistance to growth hormone, decrease

insulin and insulin-like growth factor 1, and increase cortisol levels. Although a threshold has yet to be established, low energy availability in males may also lead to decreased levels of testosterone and luteinizing hormone.

The low estrogen state of amenorrhea predisposes the female athlete to osteopenia and increases the risk of stress fractures, especially of the spine and lower extremity. If left unchecked, bone loss may be partially irreversible despite resumed menses, estrogen replacement, or calcium supplements. Similarly, low energy availability in males reduces bone turnover and can contribute to bone demineralization. Routine bone mineral density screening is not recommended but can help guide treatment and return to activity in severe cases.

Three eating disorders can occur in athletes, contributing to low energy availability. **Anorexia nervosa** manifests as weight <85% of estimated ideal body weight with evidence of starvation manifesting as bradycardia, hypothermia, and orthostatic hypotension or orthostatic tachycardia. **Bulimia nervosa** manifests as recurrent episodes (at least once weekly) of binge eating with a sense of lack of control over eating during an episode with recurrent episodes of compensatory behaviors, such as induced vomiting or excessive exercise. A third category, **unspecified feeding or eating disorder (UFED)**, is a general description for disorders failing to meet the criteria for the two previous disorders. Many young people who previously were diagnosed with UFED have a specific diagnosis of anorexia or bulimia. Signs of an eating disorder are weight loss, food restriction, depression, fatigue, worsened athletic performance, and preoccupation with calories and weight. The athlete might avoid events surrounding food consumption or might hide and discard food. Signs and symptoms include fat depletion, muscle wasting, bradycardia worsened from baseline, orthostatic hypotension, constipation, cold intolerance, hypothermia, gastric motility problems, and in some cases lanugo (see Chapter 41). Electrolyte abnormalities can lead to cardiac dysrhythmias. Psychiatric problems (depression [see Chapter 39], anxiety [see Chapter 38], and suicide risk [see Chapter 40]) are of higher incidence in this population.

For treatment of eating disorders, control of the symptoms is a central theme. The first step is confronting the athlete about the abnormal behavior and unhealthy weight. In general, exercise is not recommended if body weight is <85% of estimated ideal body weight, although there are exceptions, especially if the athlete is eumenorrheic. If the athlete is unable to gain weight with nutrition and medical counseling alone, then psychologic consultation is sought (Fig. 732.3).

Most athletes will not initially admit a problem, and many are unaware of the serious physical consequences. In some cases, athletes may have pursued athletic participation (e.g., in endurance activities) as a means to reduce or maintain a low body weight. A helpful technique in talking to these athletes is to sensitively point out performance issues. Education about decreased strength, endurance, and concentration can be a motivating factor for treatment. Often, the athlete's family needs to be involved, and the athlete should be encouraged to reveal necessary information to them. Psychology or psychiatry referral is important in the multidisciplinary approach to treatment of disordered eating. It is important for the physician to monitor the athlete's physical health while the mental health professional is caring for the mental aspects of the eating disorder.

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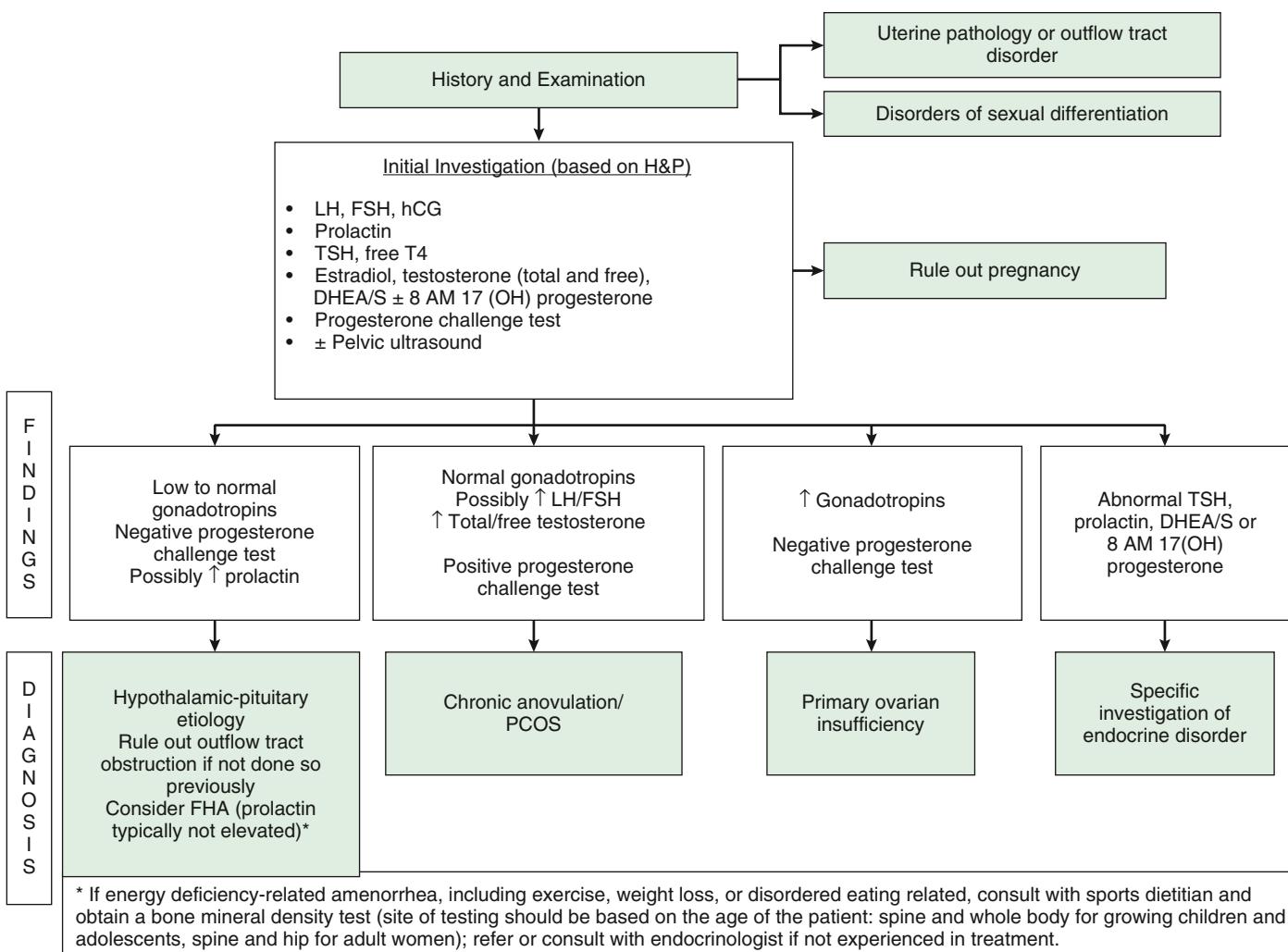


Fig. 732.2 Amenorrhea algorithm. Recommended clinical evaluation of an athlete with primary or secondary amenorrhea, or prolonged oligomenorrhea, includes a history and physical examination, initial and follow-up laboratory testing, and diagnosis by a physician. Referral or consultation with endocrinology is recommended if the diagnosing physician is not experienced with treatment of functional hypothalamic amenorrhea or other etiologies of amenorrhea. DHEA/S, Dehydroepiandrosterone sulfate; FHA, functional hypothalamic amenorrhea; FSH, follicle-stimulating hormone; hCG, human chorionic gonadotropin; LH, luteinizing hormone; PCOS, polycystic ovarian syndrome; TSH, thyroid-stimulating hormone. (Modified from Jameson JL, De Groot LJ, Illingworth P. Amenorrhea, anovulation, and dysfunctional uterine bleeding. In: Jameson JL, De Groot LJ, eds. *Endocrinology Adult and Pediatric*, 6th ed. St. Louis: Saunders, 2010: pp. 2341–2355.)

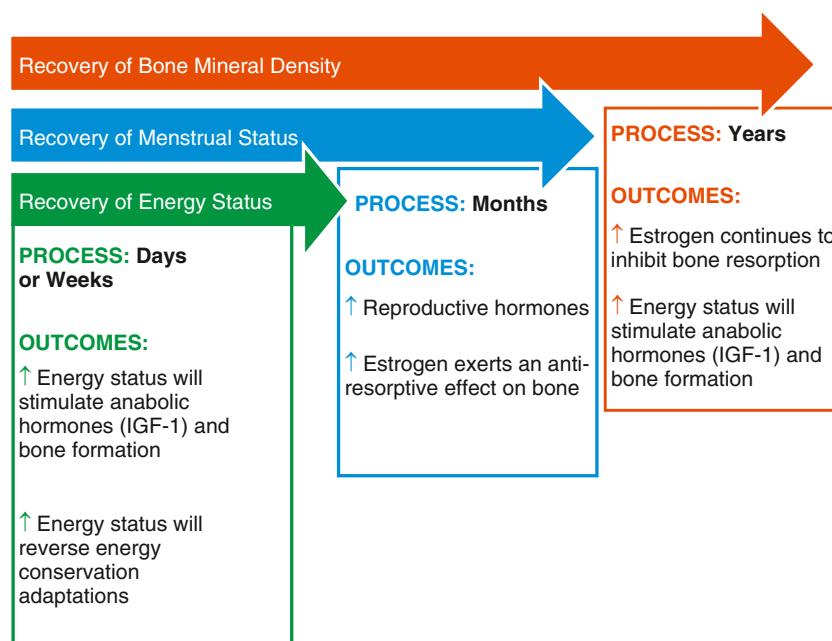


Fig. 732.3 Treatment of the female athlete triad. The three components of the triad recover at different rates with the appropriate treatment. Recovery of energy status is typically observed after days or weeks of increased energy intake and/or decreased energy expenditure. Recovery of menstrual status is typically observed after months of increased energy intake and/or decreased energy expenditure, which improves energy status. Recovery of bone mineral density may not be observed until years after recovery of energy status and menstrual status has been achieved. IGF-1, Insulin-like growth factor-1. (From De Souza MJ, Nattiv A, Joy E, et al. 2014 Female Athlete Triad Coalition consensus statement on treatment and return to play of the female athlete triad. *Br J Sports Med*. 2014;48:289. Fig. 3.)

Chapter 733

Performance-Enhancing Aids

Gregory L. Landry and Andrew M. Watson

See also Chapter 157.

Ergogenic aids are substances used for performance enhancement, most of which are unregulated supplements (Table 733.1). Many agents have significant side effects without proven ergogenic properties. The 2004 Controlled Substance Act outlawed the purchase of steroidal supplements, such as androstanediol and androstenedione, with the exception of dehydroepiandrosterone (DHEA).

The prevalence of lifetime steroid use is highest among males in the United States; among a large representative sample, 3–4% of males in middle school and 5–6% of those in high school report having used steroids for muscle enhancement. The European School Survey Project on Alcohol and Other Drugs found that 1% of European youth reported any use of steroids. Steroids in oral, injectable, and skin cream form are taken in various patterns. *Cycling* is a term used to describe taking multiple doses of steroids for a period, ceasing, and then starting again. *Stacking* refers to the use of different types of steroids in both oral and injectable forms. *Pyramiding* involves slowly increasing the steroid dose to a peak amount and then gradually tapering down.

Anabolic-androgenic steroids have been used in supraphysiologic doses for their ability to increase muscle size and strength and decrease body fat. An evidence base does support the increase in muscle mass and strength; the effects appear to be related to the myotrophic action at androgen receptors, as well as competitive antagonism at catabolism-mediating corticosteroid receptors. However, they have significant endocrinologic side effects, such as decreased sperm count and testicular atrophy in men and menstrual irregularities and virilization in women. Hepatic problems include elevated aminotransaminases and γ -glutamyl transferase, cholestatic jaundice, peliosis hepatitis, and a variety of tumors, including hepatocellular carcinoma. There is evidence that anabolic-androgenic steroids might predispose to a number of cardiovascular risk factors as well, including higher

blood pressure, lower high-density lipoprotein, higher low-density lipoprotein, higher homocysteine, and decreased glucose tolerance. The possible psychologic effects include aggression, several personality disorders, and a variety of other psychologic problems (anxiety, paranoia, mania, depression, psychosis). Physical findings that may accompany anabolic-androgenic steroid use in males include gynecomastia, testicular shrinkage, jaundice, male pattern baldness, acne, and marked striae. Women can develop hirsutism, voice deepening, clitoral hypertrophy, male-pattern baldness, acne, and marked striae.

Testosterone precursors (also known as *prohormones*) include androstanediol and DHEA. Their use in the adolescent population has increased markedly in conjunction with reports of high-profile athletes' use. They are androgenic but have not been proven to be anabolic. If they are anabolic at all, they work by increasing the production of testosterone. They also increase production of estrogenic metabolites. The side effects are similar to those of anabolic-androgenic steroids and far outweigh any ergogenic benefit. These substances cannot be sold without prescription.

Creatine is an amino acid mostly stored in skeletal muscle as creatine phosphate or phosphocreatine. Phosphocreatine has the ability to rephosphorylate adenosine diphosphate through the donation of its phosphate group, yielding creatine and adenosine triphosphate. Creatine phosphate is then reconstituted through oxidative phosphorylation. The exogenous provision of creatine can therefore allow for a greater concentration of phosphocreatine in muscle, increasing muscle performance. The use of creatine as an ergogenic aid has increased, especially since other supplements have been withdrawn from the market. Thirty percent of high school football players have used creatine. There is evidence that creatine, as a source of increased energy, enhances strength and maximal exercise performance when used during training.

Caffeine is an active ingredient in energy drinks and some endurance sport supplements that has been shown to have ergogenic effects in both aerobic and anaerobic efforts. It acts primarily as an antagonist at the adenosine receptor, resulting in a number of potentially ergogenic effects such as reduced fatigue and increased muscle power. Although moderate doses of caffeine are considered relatively safe, when included in an energy drink combined with alcohol, excessive caffeine ingestion may result in tachycardia, gastritis, nausea, vomiting, and central nervous system excitation. Overdoses of caffeine may result in seizures, arrhythmias, and hypotension.

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Table 733.1 Characteristics of Common Performance-Enhancing Substances

PERFORMANCE-ENHANCING SUBSTANCE	DESIRED EFFECTS	MAJOR ADVERSE EFFECTS	MINOR ADVERSE EFFECTS	STATUS	ROUTE OF ADMINISTRATION
Anabolic-androgenic steroids*	Increase muscle size, strength, lean body mass; decrease body fat	Testicular atrophy, CV disease, atherosclerosis, myocardial disease, liver dysfunction, cancer	Acne, gynecomastia	Banned by IOC and all major sporting bodies	Oral, topical, injectable
Creatine	Increase in strength, power output, sprint performance, total work to fatigue, peak force/power; decrease lactate threshold; increase weight and lean body mass	Heatstroke	Dehydration	Allowed	Oral

Continued

Table 733.1 Characteristics of Common Performance-Enhancing Substances—cont'd

PERFORMANCE-ENHANCING SUBSTANCE	DESIRED EFFECTS	MAJOR ADVERSE EFFECTS	MINOR ADVERSE EFFECTS	STATUS	ROUTE OF ADMINISTRATION
Human growth hormone ^t	May increase lean body mass and decrease fat mass	Carpal tunnel syndrome, intracranial hypertension, CV disease, hyperlipidemia, insulin resistance	Arthralgias	Banned by IOC and International Federations	Injectable
Amphetamines/stimulants ^{t,§}	Increase in alertness and metabolism; may increase strength, muscular power, speed, acceleration, aerobic power, anaerobic capacity, endurance	Arrhythmias, heat exhaustion, seizures, myocardial infarction, sudden death	Agitation, GI upset, nausea, headaches, insomnia, hallucinations	Banned by IOC, NCAA, NFL	Oral, injectable, inhalable
Erythropoietin/blood doping	Increase in oxygen-carrying capacity, endurance	Hypertension, myocardial infarction, pulmonary embolism, immune reaction	Headaches	Banned by IOC and all major sporting bodies	Injectable
Beta-hydroxy-beta-methylbutyrate	May increase lean body mass, muscle strength, power; enhance recovery	Unknown	Unknown	Allowed	Oral
Protein supplements	Increase lean body mass, improve healing	Unknown in previously healthy athletes	Unknown	Allowed	Oral

*Including selective androgen receptor modulators and aromatase inhibitors or estrogen receptor modulators.

^tIncluding various growth factors (IGF-1, etc.).

[‡]Caffeine is commonly used and remains permitted by WADA.

[§]Includes various beta-2-agonists prohibited by WADA, except when needed for therapy of asthma but within therapeutic limits.

CV, Cardiovascular; GI, gastrointestinal; IOC, International Olympic Committee; LDH, lactate dehydrogenase; N/A, not applicable; NCAA, National Collegiate Athletic Association; NFL, National Football League; WADA, World Anti-Doping Agency.

Modified from Momaya A, Fawal M, Estes R. Performance-enhancing substances in sports: a review of the literature. *Sports Med*. 2015;45:517–531. [Table 1](#).

Chapter 734

Specific Sports and Associated Injuries

Gregory L. Landry and Andrew M. Watson

SPORTS PARTICIPATION, EARLY SPECIALIZATION, INJURY RISK, AND BURNOUT

It is estimated that 60 million youth, age 6–18 years, participate in organized athletics, with 44 million participating in multiple sports. It has also been estimated that 69% of females and 75% of males age 8–17 years participate in at least one organized sport team or club. Participating in sport gives children the opportunity to develop self-esteem and leadership skills, promote peer socialization, and improve general health and fitness. Some parents encourage their children to participate in a *single sport* because they think this will allow the athlete more time to focus on sport-specific skills and will increase the likelihood that their child will be selected for elite teams, a college scholarship, or professional contract. They may also feel pressure from coaches. However,

only 0.2–0.5% of U.S. high school athletes rise to the professional level; Olympic-level athletes start training in their main sport at an older age than their less elite peers and on average participate in two other sports before, or in parallel with, their main sport. A study at the collegiate level revealed that 70% of surveyed athletes did not specialize in their sport until 12 years of age, and 88% participated in more than one sport at some point during childhood. *Multisport* athletes, in general, have a more diverse skill set, can transfer skills from one sport to another, have a decreased risk of **overuse injury**, have lower rates of **burnout**, and thus are less likely to quit sports at a younger age. Exposure to multiple sports also allows these athletes to identify the sport they most enjoy.

Risk of injury in sports increases with age and training volume. In general, there is an increased risk of injury if young athletes participate in more weekly organized sport hours than their age. When young athletes exceed a 2:1 ratio of weekly hours in organized sports to weekly hours in unorganized free play, they are more likely to suffer a serious overuse injury. Overuse injuries unique to young athletes include apophyseal injuries and physisal stress injuries secondary to decreased muscle mass, increased joint hypermobility, and imbalances in growth and strength (see Chapter 728). Overuse injuries and fractures are more likely to occur during adolescent growth spurts as physes, apophyses, and articular surfaces in a rapid phase of growth are less resistant to tensile, shear, and compressive forces than either mature bone or more immature prepubescent bone, and because of decreased blood flow to

the physics. When this underlying vulnerable physiology is combined with overscheduling secondary to participation in a large number of competitive events at young ages, the risk of overuse injury increases. These events often include tournaments, which may consist of multiple games in a short period of time. This type of schedule does not allow enough time for rest and recovery.

Sports specialization is traditionally defined as “participating in a single sport for greater than eight months per year, choosing a single main sport, and/or quitting all other sports to focus on one sport.” Athletes who specialize early sometimes report increased anxiety and stress secondary to worrying about failure, trying to meet adult expectations, or experiencing parental pressure to participate or perform at a certain level, and often feel as though they have a lack of control in sport decision-making. These feelings can contribute to burnout, which can lead to quitting sports early and ultimately increased inactivity as an adult. To reduce the risk of overuse injury and burnout, one should limit weekly and yearly participation time, limit sport-specific repetitive movements, and ensure adequate rest and recovery periods. Thus it has been recommended that “intense training in a single sport to the exclusion of others should be delayed until adolescence in order to optimize success while minimizing injury, stress, and burnout.”

FOOTBALL

Football is the sport with the greatest number of participants in the United States, especially at the high school level, and with the highest number and rate of injuries. Most of these injuries are relatively minor, and compared with injuries in many other sports, are less severe, as evidenced by fewer days lost from injury. Age, weight, and position played contribute to injury risk, with older and heavier players, running backs, and linebackers having higher injury rates. The most common football injuries include joint sprains, muscle strains, and contusions, with the lower extremities injured most frequently.

Although the majority of catastrophic sports injuries in the United States have occurred in football, these injuries are rare. Catastrophic injury is defined as a fatal injury or a severe injury with or without permanent severe functional disability. Disabling injuries include cervical spine and cerebral injuries.

Head and neck injuries in football include concussion, neck sprain, and brachial plexopathy. Compared to other sports, brain injury (concussion) (see Chapter 729) occurs with the highest rate in football, a result of the frequent exposure to contact during practices and games, although more concussions occur in games than practices. When compared to other sports, cervical spine injuries occur at higher rates in football given the increased risk of high-velocity contact, neck flexion, and axial loading. Proper blocking and tackling form with the neck extended rather than flexed is essential to help reduce the risk of cervical spine injury. Although not shown to reduce the concussion rate, helmets can help reduce facial and dental trauma and provide some protection from side head blows. A “**stinger**” or “**burner**” represents a brachial plexus neurapraxia (see Chapter 730). This is the most common nerve injury in football and results from traction, compression, or a direct blow to the upper cervical nerve roots of the brachial plexus caused by forceful lateral neck bending.

Heat illness is possible in pediatric athletes given physiologic factors, including increased heat production per body weight, less efficient heat dissipation, and higher body temperatures associated with dehydration. Dehydration and associated electrolyte abnormalities and poor acclimatization increase the risk of heat illness. Heat illness risk can be reduced with proper hydration prepractice, during, and post-practice, avoiding practice in high heat or humidity, wearing breathable, light-colored clothing, removing the helmet between plays, and avoiding certain medications such as antihistamines, anticholinergics, stimulants, and supplements (see Chapter 731).

Contusions to the arm or thigh muscles can result in the development of a large hematoma if not treated aggressively in the acute stage, resulting in prolonged time away from football. Large hematomas and those allowed to persist are at risk for development of **myositis ossificans**.

Low back pain can be caused by **spondylolysis**, especially in players with repetitive hyperextension of the spine (see Chapter 720.6). Education on tackling mechanics, core strengthening, and hamstring flexibility are important in prevention of and/or recovery from a spondylolysis injury. Shoulder trauma can cause glenohumeral joint dislocations, the majority of which are anterior dislocations and have a high rate of recurrence; acromioclavicular joint sprains; and fractures to the clavicle or humerus (see Chapter 724). Knee injuries (see Chapter 728.6) are common and include **anterior cruciate ligament (ACL)** tears and, less frequently, medial collateral ligament (MCL) tears. Knee bracing in high school football players is controversial and lacks significant evidence.

Ankle sprains occur frequently, with lateral ankle sprains resulting in less time away from the sport than high ankle sprains. The risk of re-injury may be reduced by rehabilitation, including strengthening and range of motion, and the use of a lace-up ankle brace (see Chapter 728.8). **Turf toe**, a sprain to the first metatarsophalangeal joint, is caused by forceful dorsiflexion of the toe while wearing soft, lightweight, flexible shoes. Calcaneal apophysitis at the insertion of the Achilles tendon on the calcaneus, also known as **Sever disease**, is an overuse injury that typically presents as heel pain in a cleated athlete who is still growing (typically age 7–10 years).

BASEBALL/SOFTBALL

Baseball- and softball-related injury sites are most commonly the shoulder, elbow, ankle, and hip. Facial injuries and concussions are also seen. The most common mechanisms of injury include pitching repetition and being hit by a ball or a bat.

Throwing injuries of the shoulder and elbow are typically seen in pitchers secondary to overuse, with contributory factors, including high pitch count, pitch type, and inadequate rest. **Little League shoulder** is a repetitive microtrauma injury to the open proximal humeral physis, and **Little League elbow** is a repetitive microtrauma injury to one or more of the six ossification centers in the elbow (see Chapter 728.3). Little League shoulder is the most common injury seen in softball windmill pitching, with similar shoulder stress as seen in overhand pitching. Poor core strength and alteration in biomechanics, especially when fatigued, may contribute to injury risk (Fig. 734.1). Age-related **pitch count** and rest guidelines, “Pitch Smart,” are available online and are endorsed by the Little League. Curve balls and sliders should not be thrown by players younger than 14 years of age. Current recommendations also advise against participating in multiple leagues and participating in year-round baseball, given the increased risk of injury with this volume of play. Adherence to the guidelines is the responsibility of the athlete, parents, and coaches. Counseling athletes (and coaches) to stop all throwing activities if the player experiences shoulder or elbow pain, with medical evaluation if no resolution with rest, is essential. If injured, a gradual return to throwing protocol under the direction of a physical therapist with additional focus on strengthening and throwing mechanics should be considered. Catchers are more vulnerable to traumatic sprains of the interphalangeal and metacarpal phalangeal joints, head injuries, including concussions from the ball striking the mask, and knee injuries associated with the deep squatting posture. Knee savers are pads attached to the shin guards that increase the angle between the knee and thigh and prevent hyperflexion of the knees. No scientific studies have been done to assess their effectiveness.

Death or serious injury in baseball is rare but may result from direct contact by the ball or bat, causing serious head injury or **commotio cordis**, which is a direct blow to the chest during a critical time in the cardiac cycle resulting in a possibly fatal arrhythmia. Batting helmets, with consideration of faceguards, must be worn properly to help prevent face and head injuries. Modifications to the hardness of baseballs used with younger athletes may also be helpful. Chest protectors have not been shown to reduce the risk of commotio cordis.

Sliding causes the most injuries in base runners, including head injury and lower limb injuries. If sliding is allowed, correct sliding technique must be taught because many injuries are secondary to timing

issues. Head-first sliding is controversial and is not recommended for players younger than 10 years of age.

BASKETBALL/VOLLEYBALL

When combining male and female sports participation, basketball has one of the highest injury rates, even though it is considered a “safe sport” from a contact perspective. Common maneuvers of basketball and volleyball include jumping, pivoting, running, and sudden acceleration and deceleration, which increase the risk for knee and ankle injuries. Similarly, injury to the fingers may result from the passing, catching, and striking of the ball inherent in these sports. Scaphoid fractures may result from falling on an outstretched hand. Injuries to the face and eyes can also occur.

Ankle sprains are the most common injury and are usually caused by inversion with plantar flexion, placing the lateral ligaments at risk. An avulsion fracture of the base of the fifth metatarsal at the insertion of the peroneus brevis tendon is another sequela of inversion ankle injuries. A **high ankle sprain** or syndesmosis ligament injury typically results from an excessive external rotation in a dorsiflexed position, and these athletes have pain out of proportion to examination findings.

Foot pain may be secondary to calcaneal apophysitis (Sever disease), retrocalcaneal bursitis, posterior tibialis tendinosis, accessory tarsal navicular, sesamoiditis, blisters, subungual hematoma, and paronychia (see Chapter 704). Achilles tendinosis is also a common overuse injury.

Knee injuries include those caused by overuse, such as traction apophysitis at the insertion of the patella tendon on the tibial tubercle (**Osgood-Schlatter disease**) (see Chapter 718.4), traction apophysitis at the distal patella (**Sinding-Larsen-Johansson syndrome**) and patellar tendinosis (**jumper’s knee**) (see Chapter 728.6).

ACL injury occurs in both male and female participants; however, among children 12–17 years old, the frequency of ACL injury in female participants is slightly higher. The exact reason for this discrepancy is unclear; however, some data suggest that female athletes do not exhibit the same neuromuscular adaptions that male athletes exhibit during pubertal growth spurts. Multiple studies on the effect of neuromuscular training and strengthening programs focused on ACL injury prevention in females suggest that these types of programs may reduce the risk of ACL injury. As with other jumping sports, other acute ligament sprains (MCL with or without ACL) can occur. For all participants, a program focused on the sport-specific strengthening of hip, core, and hamstring muscles to prevent dynamic valgus when landing can help to reduce knee injury rates.

The overhead nature of volleyball can result in overuse shoulder injuries, including rotator cuff tendinosis, shoulder impingement syndrome, labral tears, and glenohumeral instability. Players may want to limit the number of overhead spikes and serves they perform, similar to pitch count limits in baseball, to help reduce the risk of overuse

injuries. Finger injuries seen in both basketball and volleyball participants include sprains, dislocations, and fractures.

Eye injuries, although rare, can be reduced by wearing protective eyewear. Facial injuries typically result from an elbow or hand hitting the opponent’s face during rebounding or defending. Head injury can occur in both sports when the player makes contact with another player, the floor, or equipment (such as the net pole in volleyball).

TENNIS

Injury rates in high-level youth tennis players are higher than in adults. Tennis injuries occur twice as often in the lower extremity as in the upper extremity. Lower extremity injuries tend to be more acute, whereas upper extremity and trunk injuries tend to be more chronic, and the incidence of overuse injury is high. Overall injury rates are similar for males and females. However, male players age 5–10 years were more likely to sustain injuries to the head and neck and suffer injuries as a result of contact with the net, ball, or racket than other groups.

The most common injury in tennis players is to the ankle, although the knee and thigh are vulnerable as well. Lower extremity injuries are related to the frequent directional changes, creating significant concentric and eccentric loads. Overuse injuries include iliopsoas tendinitis or bursitis, patellofemoral stress syndrome, patellar tendinosis, Osgood-Schlatter disease, medial gastrocnemius strain (“**tennis leg**”), Achilles tendinitis, and Sever disease. Stress fractures in the lower extremity in elite players are most common at the tarsal navicular, metatarsals, and tibia.

In the upper extremities, **tennis elbow** (lateral epicondylitis with extensor carpi radialis brevis tendinosis) and **extensor carpi ulnaris (ECU) tendinosis** with or without subluxation, are particularly prevalent in the recreational player and are thought to be most likely related to overuse and improper technique (see Fig. 728.11). With repetitive overload of the wrist flexor-pronator muscle groups, traction apophysitis at the medial humeral epicondyle and medial epicondylar fragmentation of the humerus, especially in younger males, can occur. This can secondarily involve the ulnar collateral ligament and ulnar nerve. Shoulder pain often results from **labral injury**, a common site of injury for overhead athletes. Anteroposterior glenohumeral instability, gleno-humeral internal rotation deficit with impingement, rotator cuff strain, and scapular dyskinesis are all possible. Wrist problems include an enlarged dorsal ganglion cyst, radiocarpal joint capsular impingement or synovitis, chronic degenerative tears of the triangular fibrocartilage complex, and acute fracture of the hook of the hamate. Stress fractures may occur in the metacarpals (second metacarpal in particular) and less commonly in the humerus, ulna, and radius.

It has been hypothesized that repeated loading during service, particularly using a “topspin” serve at a young age, may contribute to the

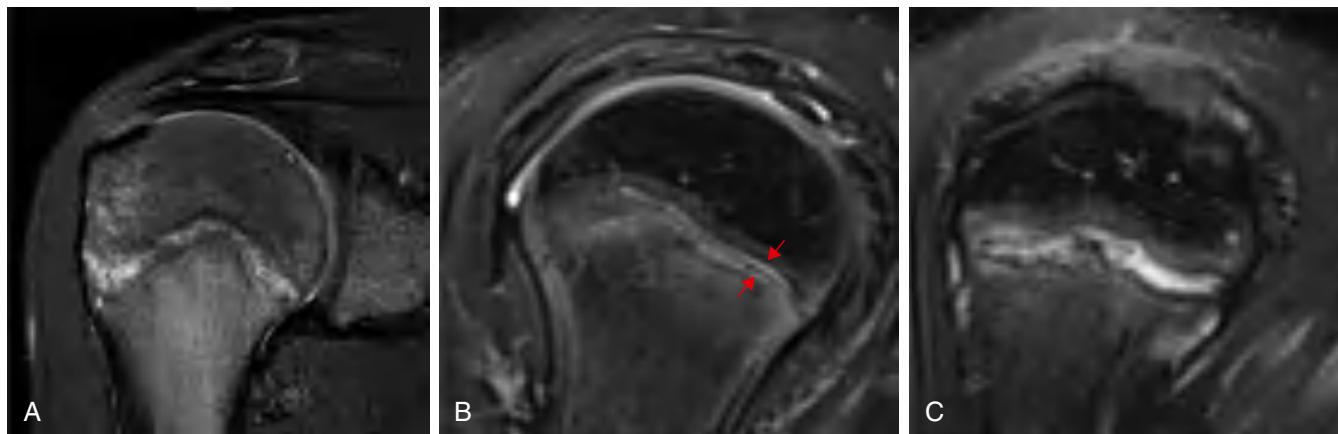


Fig. 734.1 Little League shoulder MRI findings. A, Coronal oblique fat-saturated T2 weighted image in a 12-yr-old pitcher demonstrates diffuse proximal humeral primary physseal widening and undulation with bone marrow edema within the metaphysis and lateral epiphysis. B and C Sagittal oblique fat-saturated T2 weighted images obtained in a 13-yr-old pitcher demonstrate preservation of the normal anterior medial humeral physis (arrows) in contrast to the widened irregular physis posteriorly and laterally. (From Braithwaite KA, Marshall KW. The skeletally immature and newly mature throwing athlete. Radiol Clin N Am. 2016;54:841–855.)

development of **spondylolysis (pars interarticularis fracture)** or spondylolisthesis. However, the most common back injury in tennis is lumbar muscle strain.

LACROSSE

Lacrosse is one of the fastest growing sports for both male and female youth, high school, and college level athletes. Protective equipment and rules are different for male and female players. Required equipment for male players includes mouth guard, helmet, gloves, and elbow and shoulder pads. Required equipment for female players includes eye wear and mouth guard. **Checking** is allowed in men's lacrosse but is not permitted in youth or women's games.

Injury rates are nearly three times higher in competition than in practice. The most common injuries for all players include lower extremity injuries, primarily ankle and knee sprains, and head injuries. Ankle sprains typically occur in the setting of cutting, dodging, and twisting activities. The likelihood of subsequent injury may be reduced with bracing. ACL tears are a common knee injury and typically occur in noncontact cutting or pivoting. Prepractice training should include balance, lower extremity strengthening, and neuromuscular feedback activities, as these have been proven to help reduce the ACL injury rate.

Head injury occurs in both male and female players. Player-to-player contact is the typical mechanism for head injury in male players. Incidental contact with the stick is the typical mechanism for head injury in female players. Eyewear for female athletes has been shown to reduce the risk of significant eye injury.

Upper extremity injuries include **acromioclavicular sprains** and hand and thumb fractures, particularly in games that permit contact and checking. Shoulder and elbow injuries are typically secondary to contact injury.

As with any sport with significant protective equipment that impedes heat loss, heat illness can occur. Players and coaches should be mindful of hydration, temperature, humidity, and duration of play. Commotio cordis is a rare but possible risk. The use of chest protectors has been evaluated and has not been shown to reduce risk.

SWIMMING/DIVING

In competitive swimming, injuries to the shoulder are most common and are generally a result of chronic overuse. **Swimmer's shoulder** is a general term for shoulder overuse in a swimmer and is typically a combination of subacromial impingement/bursitis and tendinosis of the rotator cuff and long head of the bicep tendon. Commonly, a narrowed subacromial space, increased laxity of the shoulder capsule, and relative weakness of the scapular stabilizers result in protracted shoulder posture, which contributes over time to the insidious onset of shoulder pain and possible **scapulohumeral dyskinesis**. Freestyle, back, and butterfly strokes tend to exacerbate the pain. Prevention includes monitoring training load, proper technique, and strengthening exercises. The multiaxial instability of the glenohumeral joint common in swimmers is addressed with rehabilitation focusing on strengthening of the rotator cuff and scapular stabilizer musculature. Knee and hip/groin pain can be exacerbated with breaststroke given the whip kick motion required in this stroke.

Swimmer's ear, or **otitis externa**, presents with pain and often drainage from the external auditory canal. It is caused by bacterial, or less commonly, fungal infection of the external auditory canal as a result of chronic, excessive wetness (see Chapter 679).

Diving is a sport that many athletes start at a young age with early sport-specific, specialized training. The most common injury for divers is shoulder strain, given overhead activity and the significant force taken by the shoulder, which is dependent on the angle of entry into the water. Low back pain can be seen in divers and may be associated with lumbar hyperextension to compensate for limited shoulder flexibility when entering the water, which can lead to spondylolysis. Diving is also associated with a risk of cervical spinal cord injury secondary to axial loading; according to the National Spinal Cord Injury Statistical Center, diving is the fifth leading cause of spinal cord injury in the United States.

SOCER

Soccer enjoys a very high level of popularity and participation among youth worldwide. In the United States, the annual rate of injury in

soccer more than doubled between 1990 and 2014, and almost three million children were seen in U.S. emergency departments for injuries related to soccer during those years. Mechanisms of injury include non-contact, body-to-body contact, falls, or ball-to-body contact. Although lower extremity injuries are by far the most common, younger children are more likely to injure an upper extremity, and upper extremity injuries are most likely to be fractures. Torso and significant abdominal injuries can occur. Low back symptoms are relatively less common and are most often muscular in nature.

Injuries in youth soccer occur predominately in the lower extremity and include joint and ligament injuries, abrasions, contusions, muscle strains, and fractures of the ankle, knee, and thigh. Ligamentous injuries to the ACL and MCL at the knee and the **anterior talofibular ligament** at the ankle can occur because of the cutting and pivoting maneuvers required during play or as a result of contact with another player. ACL injuries, particularly in females, have gained attention in recent years. ACL injuries are more common in high school girls' soccer than in other girls' sports. Risk factors may include genetics, hormones, age, sex, previous injury, and anthropomorphic factors. **Overuse syndromes** such as patellofemoral dysfunction, Osgood-Schlatter, Sinding-Larsen-Johansson, and Sever disease frequently occur. Hip problems include the **hip pointer (iliac crest contusion)**, iliac crest apophysitis, and chronic groin pain (muscle strain, **sports hernia**, **osteitis pubis**). The terms *sportsman's hernia*, *inguinal insufficiency*, and *conjoint tendon tear* may comprise a constellation of different pathologic processes producing similar groin pain. These injuries may occur with the combined forceful rotation of the torso and kicking motion. Femoral neck stress fractures, slipped femoral capital epiphysis, and avulsion fractures of the pelvis or femur should also be considered in the differential. Neuromuscular factors, such as quadriceps dominance, muscle activation patterns and dynamic stability, may be modifiable; thus the American Academy of Pediatrics (AAP), and other organizations support neuromuscular training programs aimed at risk reduction for both sexes.

Concussion is common in soccer, primarily as a result of contact between players, player and goal post, and player and ground. Recent evidence suggests that intentional heading of the ball rarely results in a concussion, although the long-term effect of repeated subconcussive impacts for intentional heading remains unknown. The U.S. Soccer Concussion Initiative updated recommendations to reduce head injury risk in youth soccer players, including a ban on heading the ball for age 10 and under and limited heading of the ball for 11-13 year olds. It remains unknown if this has reduced the number or severity of concussions. Padded headbands have not been shown to reduce the risk of concussion in youth soccer players.

ICE HOCKEY

Ice hockey is a fast-paced collision sport associated with injuries caused by contact from other players, the ice, or the boards, as well as from the puck or stick. With injury rates similar to other high school full-contact sports, concussions, contusions, fractures, ligament sprains, muscle strains, lacerations, joint separations, dislocations, and subluxations are commonly reported. Injuries are more likely to occur in competition than in practice, and overall injury rates appear to be on the rise, possibly related to increased participation.

Concussion was the most commonly reported injury in U.S. high school ice hockey athletes, with head and face injuries accounting for 34% of all of the reported injuries. Injuries to the shoulder and arm are also common and include contusions, strains, acromioclavicular separations, and clavicle fractures. Over 50% of upper extremity fractures occur in the forearm, wrist, and hand. Other specific hockey injuries include hip pain secondary to **femoroacetabular impingement (FAI)**, high ankle sprains, hip adductor strain, and **osteitis pubis**.

The role of factors such as age, size, level of skill, player position, and sex in injury risk is inconclusive, although evidence suggests that concussion may be more frequent in females and fractures more common in males.

Body checking is the single most common mechanism of injury. In Canada, 11- and 12-year-old Pee Wee hockey players who were allowed

to body check had a threefold greater risk of injury than those who were not. USA Hockey rules of play do not allow body checking in the 12-year and under youth leagues. Body checking is not allowed in girls'/women's leagues of any age. The AAP recommends the expansion of nonchecking programs and the restriction of body checking to elite levels of boys' play after 15 years of age. AAP recommendations also include the use of protective equipment (helmets and full-face shields or cages), rules to eliminate dangerous play with a zero-tolerance policy for head contact and body contact from behind, and safer play education for coaches and athletes.

FIELD HOCKEY

Field hockey is played worldwide by both male and female athletes. Protective equipment, including mouth, shin, and ankle guards, is recommended but not required. Players are twice as likely to be injured in game versus practice. Lower limb injuries, particularly inversion ankle sprains, are the most common. Bracing may help with ankle re-injury rates. Other lower extremity injuries include hamstring strain, ACL tears, and contusions. The most common upper limb injury occurs when the hand is struck by a stick or a ball, as field hockey does not require the use of padded gloves for protection. Head injury and facial lacerations occur at a very high rate and are typically caused by contact with the stick or ball. Injury types and rates may differ based on the position played; however, specific data are lacking.

Injury prevention is important in this sport and can be attained via the use of protective equipment, including permitted head or face protection, and sport-specific training, including balance, strengthening, and proprioceptive training activities.

SKIING AND SNOWBOARDING

Injury frequency in skiing, snowboarding, and related winter sports has declined over the past several decades, largely secondary to improved equipment (boots, bindings, poles) and slope conditions. Of concern, however, is that severe head and spinal cord injuries are on the rise due to increased speed and the addition of acrobatic maneuvers (terrain parks, half pipes, aerial tricks). Head and neck injuries are the primary cause of fatal injury. Of the World Cup events, freestyle skiers (particularly aerials and slope style) have a higher incidence of head injury than snowboard and alpine events. Overall, the risk of injury is higher in snowboarders, males, beginners, and those with improper equipment.

Lower extremity injuries are more commonly associated with skiing, while head, internal organ, upper extremity, and ankle injuries are more common in snowboarders. The most common lower extremity injury in skiing is ligamentous (ACL, MCL, and LCL) at the knee. Lower-extremity injuries in skiers also include contusions, knee dislocation, femur fractures, spiral fractures of the tibia (**"boot top" fractures**), and high ankle sprains. Snowboarders are at a unique risk for fracture of the lateral process of the talus, which is often initially misdiagnosed as an ankle sprain.

Upper-extremity injuries are more common in snowboarding because both of the snowboarder's feet are strapped onto the same board and, without poles, there is an increased risk of falls on outstretched arms. Common injuries include distal radial, ulnar, and metacarpal fractures, sprains, and contusions. Other high-incidence upper extremity injuries in snowboarding include shoulder soft tissue injuries, clavicle fractures, acromioclavicular sprains, and glenohumeral joint dislocations. A unique skiing injury is **skier's thumb**, a sprain of the ulnar collateral ligament of the thumb, which typically results from a fall with the thumb in abduction and hyperextension around a ski pole. Phalanx fractures and bony avulsions can also be associated with this injury.

Snow sport athletes may experience visceral injuries to the spleen, liver, and kidney. Spine injuries, including fracture and strain, may also occur.

It is strongly advised that individuals of all ages wear helmets for skiing and snowboarding. Wrist protectors are also recommended for snowboarders. Care should be taken to ensure up-to-date and properly fitted and adjusted equipment. Preventive measures endorsed by the AAP include participation in formal instruction, such as in a ski school, having adequate supervision, and exercising responsible speed and technique. Cardiovascular fitness, endurance, and muscle strength are believed to be critical components in injury prevention; however, there is limited supportive literature.

SKATEBOARDING

Injuries associated with skateboarding are predominantly acute, including contusions, lacerations, sprains, and fractures, affecting the wrists, forearms, and to a lesser extent, the ankles and head. Fractures involving the upper extremities are more common in younger skateboarders, often from a fall onto an outstretched arm. Lower-extremity fractures and head injuries predominate in the adolescent population, which is likely because of higher complexity of the airborne maneuvers and tricks often attempted. Loss of balance leading to a fall when failing to perform a particular maneuver, especially when catching a wheel, is generally the primary cause of injury. These falls can occur at high velocities (up to 40 mph), placing the skateboarder at risk for serious injuries.

Traumatic brain injuries do occur within this sport; the incidence increases with age and is more common in males than females. In older children and adolescents, the neglected use of helmets and the increased speed of their skating contribute to this fact.

In addition to helmet use, other safety measures recommended include wrist guards as well as elbow and knee pads. The building of skateboard parks has been a recent strategy to remove skateboarders from pedestrians, bicyclists, and motor vehicle traffic, while also encouraging adult supervision.

CYCLING AND MOTOCROSS

Bicycle riding has been a beloved childhood recreational activity for decades. Cycling options have expanded to include a variety of events such as track and road racing as well as mountain biking, mountain bike terrain parks or "free-riding," cyclo-cross, and freestyle BMX. As increased speed, jumps, and other human-made obstacles have been added, risk for injury has increased. Motocross, beginning as early as 4 years of age, adds further complexity as it uses two-wheeled motorized cycles racing through designed outdoor courses.

Recreational bicycling injuries include abrasions, lacerations, contusions, and fractures. Head and face as well as genitourinary injuries are common. Helmet use is strongly encouraged to reduce the risk of serious head injury. Upper extremity fractures predominate in mountain bikers and mountain terrain park riders. Risk of injury is increased in mountain biking males between 10 and 14 years and in those who admit to riding faster than usual. Motocross riders sustain more serious injuries. Head injuries include skull fractures and a variety of intracranial bleeds that may occur even when using a helmet.

WRESTLING

Wrestlers may have great fluctuations in weight to meet weight-matched competition standards. Such fluctuations are sometimes associated with fasting, dehydration, and then binging. Counseling wrestlers and their parents regarding impaired performance from these components of disordered eating, especially with respect to decreased speed and strength, is important to deter athletes from incorporating them into routine practice. Most states have rules in place to mitigate this risk by limiting the amount of weight loss for each wrestler.

Wrestling moves apply a variety of torques or forces to the extremities and spine, potentially resulting in a number of common injuries. Takedown maneuvers and subsequent impact with the mat can produce concussions, neck strain/sprain, or spinal cord injury. Spondylolysis (see Chapter 720.6) is a concern in wrestlers given repetitive lumbar extension.

Stingers and **burners**—also seen among football players—are caused by stretching or pinching of the brachial plexus (see Chapter 730). Overall, the two most common sites of injury in wrestling are the shoulder and knee.

At the shoulder, subluxation is common. This generally occurs anteriorly with the shoulder forcibly abducted and extended. Patients are commonly aware of their shoulder slipping in and out. Injuries to the hand are less common and typically include metacarpophalangeal and proximal interphalangeal joint sprains.

Knee injuries (see Chapter 728.6) are also common, and include **prepatellar bursitis**, medial and lateral collateral ligament sprains, and medial and lateral meniscus tears. Acute or recurrent traumatic impact to the mat can result in prepatellar bursitis. If the overlying skin is broken, septic bursitis may occur, resulting in swelling, redness, and warmth over the anterior knee.

Dermatologic problems associated with wrestling include herpes simplex (see Chapter 299: **herpes gladiatorium**), impetigo (see Chapter 706.1), staphylococcal furunculosis or folliculitis, superficial fungal infections, and contact dermatitis. Herpes gladiatorium and superficial bacterial skin infections are contraindications to wrestling until the lesions have resolved. Washing of the wrestling mats with appropriate antibacterial and antifungal solution is required after daily wrestling sessions to keep the mats disinfected and prevent the spread of dermatologic contagion.

Auricular hematoma is caused by friction or direct trauma to the auricle (see Chapter 683). If allowed to remain without evacuation, irreversible deformity of the auricle often results, termed cauliflower ear. Properly fitted headgear is the best means of prevention, and early aspiration of the accumulated blood may reduce the risk of deformity.

RUNNING

Running for sport and exercise has increased in popularity for children and adolescents. Running problems are typically caused by overuse injury related to muscle imbalance; a minor skeletal deformity; repetitive overload; and/or poor flexibility, strength, endurance, or proprioception. With each step while running, the foot impact ranges from 3-8 times the athlete's body weight. Errors in training, including increasing the distance or intensity of workouts too rapidly, often result in injury to the runner. Minor variations (e.g., malalignment) in anatomy that do not cause problems at rest can predispose to injury at specific sites, such as **over-pronation** contributing to increased **patellofemoral stress**. Muscle fatigue, environmental temperature (see Chapter 731), and running surface (grass vs unyielding concrete) also contribute to injury. **Barefoot** or **minimalist running** shoes may promote greater weight distribution through the forefoot during running, and biomechanical research suggests reduced joint forces through the knee and hip. However, increased forces can occur through the foot, ankle, and lower leg in individuals not accustomed to this style of running. Prevention of injuries is possible by muscle-strengthening exercises, incorporating periods of rest into training plans, and the use of good-quality running shoes that match an athlete's foot type.

Shin splints, or **medial tibial stress syndrome**, is a descriptive term for pain located diffusely over the distal medial tibia and should be distinguished from tibia stress fracture and chronic exertional compartment syndrome. Medial tibial stress syndrome is a periosteal stress reaction at the insertion of the soleus muscle. It can be seen in new runners, runners that have markedly increased their training duration in a short period of time, and runners with higher body mass indices (BMIs). Continued loading and stress of medial tibial stress syndrome can lead to a **stress fracture**. Stress fractures in runners (see Chapter 724.4) have been documented at the femoral neck, inferior pubic rami, subtrochanteric area, proximal femoral shaft, proximal tibia, fibula, calcaneus, tarsal navicular, metatarsals, and sesamoids. The most common are in the metatarsals, tibia, and fibula. The anterior proximal tibia, femoral neck (tension or superior side), tarsal navicular, and sesamoids are most at risk for nonunion.

Muscle strains most frequently affect the hamstrings, followed by the quadriceps, hip adductors, soleus, and gastrocnemius muscles. Lower extremity tendon injuries are more common than apophyseal injuries in young, skeletally immature runners. Tendon injury is most common in the Achilles tendon, followed by the posterior tibial, peroneal, iliopsoas, and proximal hamstring tendons. Achilles tendinosis should be distinguished from retrocalcaneal bursitis.

Knee pain in the runner is frequently anterior in location and is commonly caused by **patellofemoral pain syndrome (runner's knee)**, which results from excessive dynamic, usually lateral, motion of the patella in relationship to the femoral intracondylar groove (see Chapter 728.6). The athlete's body habitus (i.e., increased Q-angle, over-pronation) and presence of core and hip abductor weakness may contribute to this overuse injury. Posterior knee pain can be caused by gastrocnemius strain, while posteromedial pain may be caused by proximal tibial stress fracture or semimembranosus/semitendinosus tendinosis. Lateral knee pain is commonly caused by **iliotibial band syndrome** and less so by **popliteal tendinosis**, which may be precipitated by running downhill. Iliotibial band syndrome may combine a

component of both bursitis and tendinosis owing to mechanical friction of the iliotibial band (an extension of the tensor fasciae latae) over the lateral femoral epicondyle. Vague knee pain that worsens with activity or traumatic event, particularly if associated with joint swelling, should raise suspicion for **osteochondritis dissecans**, most commonly located at the lateral aspect of the medial femoral condyle.

Chronic exertional compartment syndrome can involve any of the muscle compartments, but the most common is the anterior compartment. There is typically poorly localized throbbing pain that begins 10-15 minutes into a run. Pain typically prevents further training, thus limiting the risk of nerve injury (see Chapter 728.7).

Plantar fasciitis is an inflammation of the supporting structures of the longitudinal arch of the foot due to repetitive cyclic loading with foot strike. Pain is typically worst with the first step out of bed in the morning and with running and is located on the medial aspect of the heel. Pes planus and over-pronation are common in these patients. Calcaneal stress fracture should be considered, especially in the amenorrheic distance runner (see Chapter 732).

The **female and male athlete triads (or relative energy deficiency in sport)**, referring to abnormalities in energy availability, endocrine function, and bone health, are well documented in adolescent running literature and are important education topics for the runner, parents, and coaches (see Chapter 732).

CHEERLEADING

Like other sports, cheerleading has become increasingly popular and evolved to become more competitive and athletic. Cheerleading can begin as early as 3-6 years of age and includes skill levels ranging from recreational to sideline, competition to professional. The sport includes advanced gymnastic tumbling and "stunts" involving athletes lifting and throwing other athletes overhead. This requires repetitive flexion, hyperextension, and rotation of the spine as well as compressive loading on landings, and the risk of athlete contact and falls.

Stunting injuries account for the majority of injuries, with bases (the athletes who lift, throw, and catch another athlete) at higher risk of injury than fliers (athletes who are lifted and thrown). The primary mechanism of injury is contact with another athlete. Injuries sustained in tumbling are the second most common.

The overall injury rate in cheerleading is low at 1/1,000 athletic exposures. However, injuries may be severe; of all female sports, the risk of catastrophic injury is the highest in cheerleading. Following a period of increasing incidence of injury, it appears that injury rates have stabilized.

Head and facial injury accounts for almost one third of injuries sustained. Head trauma primarily results from falls while stunting or from a pyramid formation, which includes the base cheerleaders as well. After concussion, strains and sprains account for the most likely injuries, with ankle the most common site followed by wrist and trunk. Fractures are more likely to occur in the upper extremity. Overuse injuries are common.

Strategies to reduce the risk of injury include designating cheerleading as an official sport, ensuring athletes undergo preparticipation exams, participating in conditioning and strength training, using proper lifting technique, avoiding stunting over hard surfaces, and educating coaches and trainers about sport safety, including specific rules for the execution of technical skills. The American Association of Cheerleading Coaches and Administrators and others have also set up rules to limit the type of stunts performed, and the National Federation of State High School Associations annually updates rules for spirit events with the intent of improving cheerleading safety.

GYMNASICS

Typically, males and females begin gymnastics participation at 4-5 years of age. The highest level of competition is in the mid-teens followed by retirement, often by 20 years of age for females and mid-20s for males. Both acute and chronic injuries, with a high incidence of overuse-related injuries, are seen in gymnasts and commonly involve the wrists, shoulders, ankles, and back. Injury types and rates in the acrobatic and circus arts are similar to those seen in traditional gymnastics.

The injury rate is similar in male versus female gymnasts. Lower-extremity injuries are more common in female gymnasts, whereas upper body injuries occur with higher frequency in male gymnasts.

Apparatus competed upon accounts for this discrepancy, such as the horizontal bar and ring exercises for male gymnasts, which place a great deal of stress upon the shoulders, and floor exercise, vault, and balance beam for female gymnasts, stressing the feet and ankles. In addition to mechanical or traumatic injuries, female gymnasts may have delayed menarche and can be at risk for hypothalamic amenorrhea or oligomenorrhea, as well as low body weight for height, which is related to disordered eating. Despite the presence of these two components of the **female athlete triad** (see Chapter 732), the third component, reduced bone density or osteoporosis, is not commonly seen. In fact, bone density tends to be high in most gymnasts, which is thought to be secondary to their performance involving repetitive high-impact activities. Nevertheless, **stress fractures**, in both the upper and lower extremities, are a significant problem. The short stature associated with male and female gymnasts is probably caused by selection bias and not the result of gymnastics training.

The amount of weight bearing through the upper extremities in gymnastics can contribute to the development of both traumatic and overuse injuries. During upper extremity weight bearing, the wrist, particularly over the radial physis, is subjected to a force almost twice the athlete's body weight and up to 16 times the body weight during high-impact loading activities. This, along with repetitive motion, axial compression, and torsional forces, contributes to the increasing frequency of wrist pain and injury in gymnastics and acrobatics. Wrist pain and injury is also correlated with training intensity, based on skill level and number of hours of training per week. Wrist injuries typically seen include **distal radial epiphysitis (gymnast's wrist)**, triangular fibrocartilage complex tears, scaphoid fractures, **scapholunate dissociation**, dorsal ganglion cysts, and wrist sprains (see Chapter 722). Individualized training regimens, including gradual increase in training load and reduced training during growth spurts, as well as the use of wrist orthoses, should be considered for these athletes.

Ankle sprain remains the most common injury in gymnastics, secondary to forces seen in landing and dismounting. Ankle sprains that have not responded to conservative management should be further evaluated for osteochondral defects of the talar dome. Heel pain may be secondary to plantar fasciitis, Sever disease, or calcaneal stress fracture. Patellar tendinopathy may contribute to knee pain in a gymnast.

Spine injuries are notable for a high incidence of **spondylolysis**, a stress fracture of the pars interarticularis, and, in less frequent cases, spondylolisthesis, both related to repetitive extension loading of spine (see Chapter 720.6). Other potential sources of back pain in a gymnast include intervertebral disk pathology, **Scheuermann disease** (juvenile kyphosis) (see Chapter 720.4), and mechanical back pain secondary to biomechanical imbalances.

DANCE

Dance, including ballet, modern dance, or drill line, is a highly demanding activity that may be associated with delayed menarche in females and disordered eating in both female and male dancers (see Chapter 732). Acute injuries commonly involve the lower extremities. Overuse injuries are common, due to the repetitive nature of maneuvers incorporated into training and performance and occur at the same rate in amateur male and female dancers. Injuries seen in modern/contemporary dance are similar in type and incidence to those seen in traditional ballet.

Frequently, kinetic chain dysfunction contributes to injury and should be considered when evaluating the dancer. Common mistakes in technique can cause injury, such as forcing excessive "turnout" (external rotation at the hip) in ballet resulting in undue stress placed upon the hip and knees (see Chapter 728.6).

Foot problems are common and include metatarsal stress fractures, subungual hematomas, **sesamoiditis**, **tenosynovitis** (especially of the flexor digitorum longus), plantar fasciitis, Achilles tendinitis, retrocalcaneal bursitis, calluses, and bunions (see Chapter 728.7). A **dancer's fracture** is an avulsion fracture of the distal shaft of the fifth metatarsal. This fracture is at risk for delayed

healing as a result of the tenuous blood supply in the area and may necessitate surgical fixation. Common ankle injuries and pain include acute sprains, anterior and posterior impingement syndromes, and osteochondral defects of the talus. Soft tissue impingement between the lateral malleolus and talus can cause persistent pain after an inversion injury. Medial tibial stress syndrome ("shin splints") and tibial stress fractures are noted in the lower leg. Achilles tendinopathy is seen due to the demands of running and jumping. Patellar malalignment or hypermobility can result in patellofemoral pain syndrome or, less frequently, patellar subluxation/dislocation. Patellar tendinopathy is widely reported. **Internal snapping hip syndrome**, caused by the iliopsoas tendon riding over the anterior hip capsule and iliopectineal eminence, and hip flexor (rectus femoris and iliopsoas) tendinosis are commonly noted in traditional ballet. Gluteal region pain with sciatica may be a result of piriformis syndrome, which occurs because of the repetitive external hip rotation required in ballet (see Chapter 728.5).

The proper time to allow a ballet dancer to go en pointe is a common question asked by dancers and parents alike. The average age to go en pointe is 12 years. A functional test should be part of that decision: if the young dancer is able to perform a passé steadily away from the barre and maintain an en pointe position without pain or instability, the dancer is likely ready to begin dancing en pointe. **Posterior impingement syndrome** of the ankle can be seen with dancing en pointe, given compression between bony or soft tissue structures during terminal plantarflexion. An **os trigonum** is commonly the cause of bony-related posterior impingement syndrome.

ADAPTIVE SPORTS

Participation in sports and recreational activities helps to minimize deconditioning; improve strength, endurance, and cardiopulmonary fitness; and promote companionship, sense of achievement, and self-esteem (see Chapter 756). Participation can also support the development of the child's motor coordination and adjustment to physical limitations. However, children with disabilities tend to participate less in physical activity for myriad reasons, including lack of access to activities or opportunities for participation, lack of self-confidence, and fear of injury by the child, parent, or physician. Direction into appropriate sports/physical activity rather than excluding them should be guided by the child's physical or mental challenge, physical abilities, preparticipation exam, and consideration of the American Academy of Orthopedic Surgeons "participation possibility chart," which outlines recommended sports and recreation based on physical disability.

Fear of injury remains a barrier to participation for many; however, the risk of injury for an adaptive sport athlete is no greater than for an athlete without disability. Injuries in the adaptive sport athlete are influenced by the specific disability, equipment used, and prosthetic or orthotics worn. Acute soft tissue injuries, including skin abrasions, contusions, sprains, and strains, tend to be the most common injuries; fractures and dislocations tend to be uncommon, given the lower participation in contact sports. Overuse injuries commonly occur in this athlete population. Lower limb injuries are more common in athletes with amputations or cerebral palsy, and upper limb injuries are more common in spinal cord injury and wheelchair-based athletes. Appropriate training to support muscle balance and avoid muscle imbalance, as well as the management of **spasticity** and properly fitting prosthetics and orthotics can help to reduce the risk of overuse injuries. Pressure sores are common in wheelchair-based athletes and can be avoided with vigilant skin care and monitoring and weight shifting.

Consideration of the athlete's disability and medications is essential because they may have increased propensity for abnormalities in, for example, thermoregulation, resulting in heat illness, and fluid and electrolyte derangements. This should be discussed and monitored with the athlete, parents, athletic trainers, and coaches, as appropriate.

Section 3

The Skeletal Dysplasias

Chapter 735

General Considerations in Skeletal Dysplasias

Julie E. Hoover-Fong and Daniah Albokhari

Genetic skeletal disorders include skeletal dysplasias, as well as metabolic bone conditions, dysostoses, and other skeletal malformations (Table 735.1).

The **chondroosteodysplasias**, also known as **skeletal dysplasias** or bone dysplasias, are a genetically and clinically heterogeneous group of disorders with an estimated prevalence of 1/4,000 births. The chondroosteodysplasias can be divided into the chondrodysplasias and osteodysplasias. The former includes genetic disorders of cartilage and results in deficient linear growth, typified by achondroplasia. The **osteodysplasias** are marked by abnormal bone structure, with a classic example of osteogenesis imperfecta (see Chapter 742). The clinical picture of the chondroosteodysplasias is dominated by generalized skeletal abnormalities with frequent involvement of nonskeletal elements. The disorders range in severity from lethal in utero to such mild features as to go undetected. Metabolic bone conditions, such as rickets or hypophosphatasia, are because of abnormal bone mineralization, whereas the dysostoses affect a single bone (e.g., craniosynostosis). Many complex genetic syndromes include skeletal malformations as part of the overall phenotype.

The chondrodysplasias are distinguished from other forms of short stature by skeletal disproportion between the length of the torso and the limbs. There are two basic categories of skeletal dysplasias: those with predominantly short limbs versus short trunks. Figure 735.1 notes the importance of cartilage in bone formation. Efforts to define the extent of clinical heterogeneity has resulted in the delineation of well

Table 735.1 Nosology of Genetic Skeletal Disorders: 2023

GROUP #	NAME	EXAMPLES*
01	FGFR3 chondrodysplasias	Achondroplasia, hypochondroplasia, thanatophoric dysplasia type 1, 2
02	Type 2 collagen disorders	Achondrogenesis (<i>COL2A1</i>), Kniest dysplasia, Stickler syndrome (<i>COL2A1</i> related)
03	Type 11 collagen	Stickler syndrome (<i>COL11A1</i> , <i>COL11A2</i>), Marshall syndrome
04	Sulfation disorders	Achondrogenesis (<i>SLC26A2</i>), diastrophic dysplasia, spondyloepimetaphyseal dysplasia
05	Dysplasias with multiple joint dislocations	Ehlers-Danlos syndrome types 1 and 2, SEMD with joint laxity
06	Filamins and related disorders	Frontometaphyseal dysplasias (multiple types), Larsen syndrome
07	Proteoglycan core protein disorders	Spondyloepiphyseal dysplasias (multiple types)
08	TRPV4 disorders	Metatropic dysplasia, spondyloepiphyseal dysplasia, SEMD
09	Pseudoachondroplasia and the multiple epiphyseal dysplasias	Sticker syndromes (multiple types), MED (multiple types)
10	Skeletal disorders caused by abnormalities of cilia or ciliary signaling	Short-rib polydactyl syndromes (Jeune syndromes multiple types), Ellis-Van Creveld syndrome, Meckel syndrome
11	Metaphyseal dysplasias	Metaphyseal dysplasia (multiple types)
12	Spondylometaphyseal dysplasias	Spondylometaphyseal dysplasias (multiple types)
13	Spondyloepi(meta)physeal dysplasias	Multiple types
14	Severe spondylodysplastic dysplasias	Achondrogenesis (<i>TRIP11</i>), spondylometaphyseal dysplasia (<i>GPX4</i> , <i>SBDS</i> , <i>PAM16</i>)
15	Mesomelic and rhizo-mesomelic dysplasias	Robinow syndrome (multiple types), mesomelic dysplasia (multiple types)
16	Acromesomelic dysplasias	Multiple types
17	Acromelic dysplasias	Geleophysic dysplasias, acromicric dysplasias, Weill-Marchesani syndrome (multiple types)
18	Brachydactylies (isolated)	Multiple types
19	Brachydactylies (syndromic)	Multiple types, Coffin-Siris syndrome (multiple types)
20	Bent bones dysplasias	Campomelic dysplasia, bent bone dysplasia
21	Primordial dwarfism and slender bones	Microcephalic osteodysplastic primordial dwarfism (multiple types)
22	Lysosomal storage diseases with skeletal involvement	Mucopolysaccharidosis types 1, 2, 3, 4, 6, 7, 10
23	Chondrodysplasia punctata (CDP)	Rhizomelic CDP (multiple types)

Continued

Table 735.1 Nosology of Genetic Skeletal Disorders: 2023—cont'd

GROUP #	NAME	EXAMPLES*
24	Osteopetrosis and related osteoclast disorders	Osteopetrosis (multiple types)
25	Osteosclerotic disorders	Caffey disease and dysplasia, craniometaphyseal dysplasias
26	Osteogenesis imperfecta (OI) and bone fragility	OI (multiple types), osteoporosis (multiple types)
27	Disorders of bone mineralization	Hypophosphatasia, hypophosphatemic rickets (multiple types)
28	Skeletal disorders of parathyroid hormone signaling	Metaphyseal dysplasia (<i>PTHR1, SIK3</i>)
29	Osteolysis	Progeria, mandibuloacral dysplasias (multiple types)
30	Disorganized development of skeletal components	Cherubism, fibrodysplasia ossificans progressiva
31	Overgrowth and segmental overgrowth	Marfan syndrome, Loeys-Dietz syndrome, Sotos syndrome, Proteus syndrome
32	Genetic inflammatory or rheumatoid-like osteoarthropathies	Neonatal onset multisystem inflammatory disease
33	Cleidocranial dysplasias (CD)	CD (<i>RUNX2, CBF</i> B)
34	Syndromes with craniosynostosis	Carpenter syndromes, Crouzon syndromes, Pfeiffer syndromes
35	Craniofacial dysostosis	Treacher Collins syndrome (multiple types), frontonasal dysplasias; mandibulofacial dysostosis (multiple types)
36	Vertebral and costal dysostosis	Spondylocostal dysostosis (multiple types), Klippel-Feil syndrome (multiple types)
37	Patellar dysostosis	Nail patella syndrome, Holt-Oram syndromes
38	Limb hypoplasia (reduction defects)	Holt-Oram, Cornelia de Lange syndrome (multiple types) Rothmund-Thompson syndrome, Poland syndrome, TAR syndrome
39	Split hand / foot ± other manifestations	Ectodactyly-ectodermal dysplasia-cleft palate, split hand-foot malformation (multiple types)
40	Polydactyly-syndactyly triphalangism	Preaxial polydactyly (multiple types), syndactyly types 1, 3, 4, 5
41	Defects in joint formation and synostosis	Multiple synostosis syndrome (multiple types), radio-ulnar synostosis (multiple types)

*Examples are not all inclusive; incomplete list.

SEMD, spondyloepimetaphyseal dysplasia; MED multiple epiphyseal dysplasia; () gene notations in italics; TAR, thrombocytopenia absent radius.

Data from Unger S, Ferreira CR, Mortier GR, et al. Nosology of genetic skeletal disorders: 2023 revision. *Am J Med Genet* 2023;1-46 (Table 1).

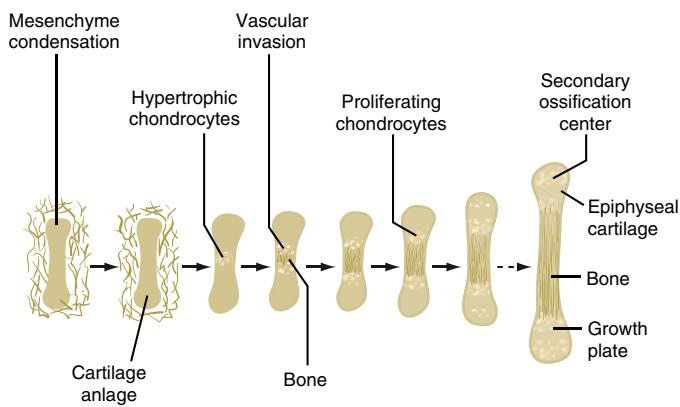


Fig. 735.1 The importance of cartilage in bone formation. (From Horton WA. Skeletal development: insights from targeting the mouse genome. *Lancet*. 2005;362:560.)

over 200 distinct entities (Table 735.2). Many of these disorders result from pathogenic variants of a relatively small group of genes, the *chondrodysplasia genes*. The better-defined chondrodysplasia groups, such as the *FGFR3* and type II collagenopathy groups, contain graded series of disorders that range from severe to mild. This severity spectrum

is increasingly appreciated in other skeletal dysplasia groups as more pathogenic variants have been discovered and their associated phenotypes defined. For some genes, such as *COL2A1*, pathogenic variants are distributed throughout the gene, and the clinical phenotypes merge into one another across a broad range. There is much less phenotypic overlap in other genes, such as *FGFR3*, in which the distribution of pathogenic variants is more discrete.

Most chondrodysplasias require the analysis of information from the history, physical examination, skeletal radiographs, family history, and laboratory testing to make a diagnosis. The process involves recognizing complex patterns that are characteristic of the different disorders (Tables 735.3–735.6). Metaphyseal dysplasias, for example, often are characterized by short stature, bowing of the legs, and a waddling gait. Most metaphyseal dysplasias have normal serum levels of calcium and phosphate, alkaline phosphatase activity, and vitamin D metabolites. In addition, subtypes of metaphyseal dysplasias exist and have their own unique features. Metaphyseal chondrodysplasia (**Jansen type**; see Chapter 737) is typified by cupped and ragged metaphyses, which develop mottled calcification at the distal ends of bone over time (Fig. 735.2). Hypercalcemia can occur. The **Schmid type** of metaphyseal chondrodysplasia is less severe, although the radiographic appearance of the knees and extreme bowing of the lower limbs resemble that in patients with familial hypophosphatemia. This condition is associated with defects in collagen type X (*COL10A1*), and the hip abnormalities are more debilitating than in Jansen metaphyseal chondrodysplasia. Patients with both types of metaphyseal chondrodysplasia have short stature.

Table 735.2 Genetics of Some Skeletal Dysplasias

GENE LOCUS	PROTEIN	PROTEIN FUNCTION	CLINICAL PHENOTYPE	INHERIT
COL2A1	Type II collagen α_1 chain	Cartilage matrix protein	Achondrogenesis II	AD*
			Hypochondrogenesis	AD*
			SED congenita	AD
			Kniest dysplasia	AD
			Late-onset SED	AD
			Stickler dysplasia	AD
ACG1	Aggrecan	Cartilage matrix protein	SED Kimberley	AD
			SEMD Aggrecan type	AR
SEDL	Sedlin	Intracellular transporter	X-linked SED tarda	XLR
COL11A1	Type XI collagen α_1 chain	Cartilage matrix protein	OSMEDA	AD
COL11A2	Type XI collagen α_2 chain	Cartilage matrix protein	OSMEDB	AR
COMP	Cartilage oligomeric matrix protein	Cartilage matrix protein	Pseudoachondroplasia	AD
			EDM1 (MED)	AD
COL9A2	Type IX collagen α_2 chain	Cartilage matrix protein	EDM2 (MED)	AD
COL9A3	Type IX collagen α_3 chain	Cartilage matrix protein	EDM3 (MED)	AD
MATN3	Matrilin-3	Cartilage matrix protein	EDM5 (MED)	AD
COL10A1	Type X collagen α_1 chain	Hypertrophic cartilage matrix protein	Schmid metaphyseal chondrodysplasia	AD
FGFR3	FGF receptor 3	Tyrosine kinase receptor for FGFs	Thanatophoric dysplasia I	AD*
			Thanatophoric dysplasia II	AD*
			Achondroplasia	AD
			Hypochondroplasia	AD
PTHR1	PTHRP receptor	G protein-coupled receptor for PTH and PTHrP	Jansen metaphyseal chondrodysplasia	AD
DTDST	DTD sulfate transporter	Transmembrane sulfate transporter	Achondrogenesis 1B	AR*
			Atelosteogenesis II	AR*
			Diastrophic dysplasia	AR
SOX9	SRY box 9	Transcription factor	Campomelic dysplasia	AD
RUNX2 ^t	Runt-related transcription factor 2	Transcription factor	Cleidocranial dysplasia	AD
LMX1B		Transcription factor	Nail-patella dysplasia	AD
CTSK	Cathepsin K	Enzyme	Pyknodysostosis	AR
RMPR	Mitochondrial RNA-processing endoribonuclease	RNA-processing enzyme	CHH	AR
DYNC2H1	Dynein, cytoplasmic two, heavy chain 1	Cytoplasmic cilia-related protein	ATD	AR
			SRPIII	AR
TRPV4	Calcium-permeable TRP ion channel	Transmembrane channel protein	Brachyolmia type 3	AD
			SMDK	AD
			Metatropic dysplasia	AD

^{*}Usually lethal.^tAlso called CBFA1.

AD, Autosomal dominant; SED, spondyloepiphyseal dysplasia; SEMD, spondylopemaphyseal dysplasia; AR, autosomal recessive; EDM (MED), multiple epiphyseal dysplasia; FGF, fibroblast growth factor; OSMEDA, otospondylomegapephysisal dysplasia autosomal dominant; OSMEB, otospondylomegapephysisal dysplasia autosomal recessive; PTHrP, parathyroid hormone-related protein; PTH, parathyroid hormone; DTD, diastrophic dysplasia; SRY, sex-determining region of the Y chromosome; CHH, cartilage-hair hypoplasia; ATD, Jeune asphyxiating thoracic dystrophy; SRPIII, short rib polydactyly syndrome type III; TRPV4, transient receptor potential vanilloid family 4; SMDK, spondylopemaphyseal dysplasia Kozlowski type.

Table 735.3 Major Problems Associated with Skeletal Dysplasias	
PROBLEM	EXAMPLE
Lethality*	Thanatophoric dysplasia
Associated anomalies†	Ellis-van Creveld syndrome
Short stature	Common to almost all
Cervical spine dislocations	Larsen syndrome
Severe limb bowing	Metaphyseal dysplasia, Schmid type
Spine curvatures	Metatropic dysplasia
Clubfeet	Diastrophic dysplasia
Fractures	Osteogenesis imperfecta
Pneumonias, aspirations	Campomelic dysplasia
Spinal cord compression	Achondroplasia
Joint problems (hips, knees)	Most skeletal dysplasias
Hearing loss	Common (greatest with cleft palate)
Myopia/cataracts	Stickler syndrome
Immunodeficiency	Cartilage-hair hypoplasia, Schimke immunoosseous dysplasia, spondyloenchondromatosis, pathogenic variants in <i>PEM3</i> , <i>EXTL3</i> , <i>ADA</i>
Poor body image	Variable, but common to all
Sex reversal	Campomelic dysplasia

*Mostly a result of severely reduced size of thorax.

†See Table 735.4.

Comprehensive descriptions of disorders and references can be found at the Online Mendelian Inheritance in Man (OMIM) website (<http://omim.org/about>), along with the most recent nosology for genetic skeletal conditions.

CLINICAL MANIFESTATIONS

Growth

The hallmark of the chondrodysplasias is disproportionate short stature. Although this refers to a disproportion between the limbs and the trunk, most disorders exhibit some shortening of both, and subtle degrees of disproportion may be difficult to appreciate, especially in premature, obese, or edematous infants. Disproportionate shortening of the limbs should be suspected if the upper limbs do not reach the mid-pelvis in infancy or the upper thigh after infancy. Disproportionate shortening of the trunk is indicated by a short neck, small chest, and protuberant abdomen. Skeletal disproportion is usually accompanied by short stature (length and height below the third percentile); these measurements are occasionally within the low-normal range early in the course of certain conditions.

There may also be disproportionate shortening of different segments of the limbs; the specific pattern can provide clues for diagnoses. Shortening is greatest in the proximal segments (upper arms and legs) in achondroplasia; this is termed **rhizomelic shortening**. Disproportionate shortening of the middle segments (forearms and lower legs) is called **mesomelic shortening**; **acromelic** shortening involves the hands and feet.

With some exceptions, there is a strong correlation between the age when shortening is appreciated and the clinical severity of the condition. Many of the lethal neonatal chondrodysplasias are evident during routine fetal ultrasound examinations performed at the end of the first trimester of gestation (see Table 735.5). Gestational standards exist

Table 735.4 Associated Anomalies in Skeletal Dysplasias	
ANOMALY	EXAMPLE
Heart defects	Ellis-van Creveld syndrome, Jeune syndrome
Polydactyly	Short rib polydactyly, Majewski type
Cleft palate	Diastrophic dysplasia
Ear cysts	Diastrophic dysplasia
Spinal cord compression	Achondroplasia
Encephalocele	Dyssegmental dysplasia
Hemivertebrae	Dyssegmental dysplasia
Micrognathia	Campomelic dysplasia
Nail dysplasia	Ellis-van Creveld syndrome
Conical teeth, oligodontia	Ellis-van Creveld syndrome
Multiple oral frenula	Ellis-van Creveld syndrome
Dentinogenesis imperfecta	Osteogenesis imperfecta
Pretibial skin dimples	Campomelic dysplasia
Cataracts, retinal detachment	Stickler syndrome
Intestinal atresia	Saldino-Noonan syndrome
Renal cysts	Saldino-Noonan syndrome
Camptodactyly	Diastrophic dysplasia
Craniosynostosis	Thanatophoric dysplasia
Ichthyosis	Chondrodystrophy punctata
Hitchhiker thumb	Diastrophic dysplasia
Sparse scalp hair	Cartilage-hair hypoplasia
Hypertelorism	Robinow syndrome
Hypoplastic nasal bridge	Acrodysostosis
Clavicular agenesis	Cleidocranial dysplasia
Genital hypoplasia	Robinow syndrome
Tail	Metatropic dysplasia
Omphalocele	Beemer-Langer syndrome
Blue sclera	Osteogenesis imperfecta

for long-bone lengths, and discrepancies are often detected between biparietal diameter of the skull and long-bone lengths. Many disorders become apparent around the time of birth whereas others manifest during the first year of life. A number of disorders manifest in early childhood and a few in late childhood or later.

Non-Growth-Related Manifestations

Most patients also have problems unrelated to growth. Skeletal deformities, such as abnormal joint mobility, protuberances at and around joints, and angular deformities, are common and usually symmetric. Skeletal abnormalities can adversely affect nonskeletal tissues. Impaired growth at the base of the skull and of vertebral pedicles reduces the size of the spinal canal in achondroplasia and can contribute to spinal cord compression. Short ribs reduce thoracic volume, which can compromise breathing in patients with short trunk chondrodysplasias. Cleft palate (see Chapter 356) is common to many disorders, presumably reflecting defective palatal growth.

Manifestations may be unrelated to the skeleton; they reflect the expression of pathogenic gene variants in nonskeletal tissues. Examples include retinal detachment in spondyloepiphyseal

Table 735.5 Lethal Neonatal Skeletal Dysplasias**USUALLY FATAL***

- Achondrogenesis (different types)
- Thanatophoric dysplasia
- Short rib polydactyl (different types)
- Homozygous achondroplasia
- Campomelic dysplasia
- Dyssegmental dysplasia, Silverman-Handmaker type
- Osteogenesis imperfecta, type II
- Hypophosphatasia (perinatal form)
- Chondrodysplasia punctata (rhizomelic form)

OFTEN FATAL

- Asphyxiating thoracic dysplasia (Jeune syndrome)

OCCASIONALLY FATAL

- Ellis-van Creveld syndrome
- Diastrophic dysplasia
- Metatropic dwarfism
- Kniest dysplasia

*A few prolonged survivors have been reported in most of these disorders.

Table 735.6 Usually Nonlethal Dwarfining Conditions Recognizable at Birth or Within the First Few Months of Life**MOST COMMON**

- Achondroplasia
- Osteogenesis imperfecta (types I, III, IV)
- Spondyloepiphyseal dysplasia congenita
- Diastrophic dysplasia
- Ellis-van Creveld syndrome

LESS COMMON

- Chondrodysplasia punctata (some forms)
- Kniest dysplasia
- Metatropic dysplasia
- Langer mesomelic dysplasia

dysplasia congenita, sex reversal in campomelic dysplasia, congenital heart malformations in Ellis-van Creveld syndrome, immunodeficiency in cartilage-hair hypoplasia, and renal dysfunction in asphyxiating thoracic dysplasia. These nonskeletal problems provide valuable clues to specific diagnoses and must be managed clinically (see Table 735.4).

Family and Reproductive History

A family history might identify relatives with the condition, and a Mendelian inheritance pattern may be elicited. Because the presentation can vary in some disorders within and among families, features that might be related to the disorder should be identified. Special attention should be given to mild degrees of short stature, disproportion, deformities, and other manifestations (e.g., precocious osteoarthritis) because they may be overlooked. Physical examination of relatives may be useful, as may the review of their photographs, radiographs, and medical and laboratory records.

A reproductive history might reveal previous stillbirths, fetal losses, and other abnormal pregnancy outcomes resulting from a skeletal dysplasia. Pregnancy complications, such as polyhydramnios or reduced fetal movement, are common in bone dysplasias, especially neonatal lethal variants.

Even though most of the skeletal dysplasias are genetic, it is common for an affected individual to be the first in their family to have the diagnosis. New pathogenic variants are common for autosomal dominant disorders, especially lethal disorders in the perinatal period (e.g., thanatophoric dysplasia, osteogenesis imperfecta). In achondroplasia, the most common short stature skeletal dysplasia, ~80% of all individuals have a new pathogenic variant in *FGFR3*. Germ cell mosaicism, in which a parent has clones of mutant germ cells, has been observed in osteogenesis imperfecta, achondroplasia, and in other dominant disorders. A negative family history is usually seen in recessive disorders unless consanguinity is present. A few of the short stature skeletal dysplasias are X-linked in origin. Prenatal diagnosis is available for disorders that have a known genetic etiology. Appropriateness of the testing depends on many factors, and genetic counseling is warranted for these families.



Fig. 735.2 Radiographic findings in Jansen-type metaphyseal chondrodysplasia. A, At age 1 yr, there is severe metaphyseal cupping and splaying at the wrists and also in the hand bones. B, At age 7 yr, there is increasing metaphyseal change at the wrists with enlarged epiphysis; enlarged epiphyses with wide epiphyseal plates are also present in the hands. C, At age 1 yr, there are severe metaphyseal irregularities at the knees and ankles (femur, tibia, and fibula) and enlarged, rounded epiphyses. D, At age 7 yr, there are severely fragmented, sclerotic metaphyses, wide epiphyseal plates, and enlarged epiphyses. Radiographic findings in Jansen-type metaphyseal chondrodysplasia. (From Slovis T, ed. Caffey's Pediatric Diagnostic Imaging, 11th ed. Philadelphia: Mosby, 2008.)

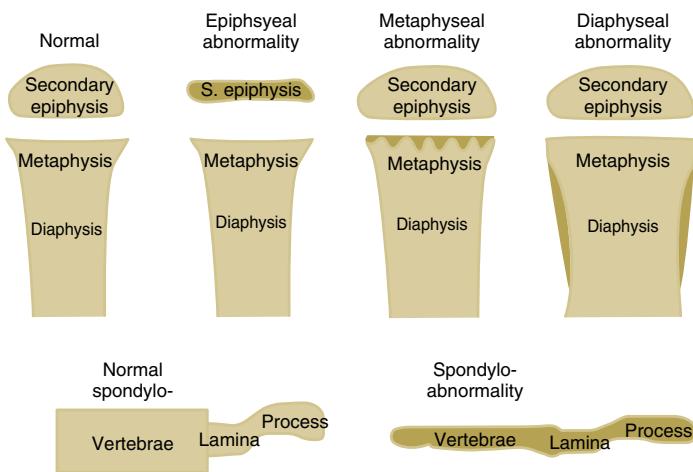


Fig. 735.3 Demonstration of the different portions of the appendicular skeleton that manifest radiographic abnormalities that aid in the clinical classification of the skeletal dysplasias. (From Krakow D, Rimoin DL. The skeletal dysplasias. *Genet Med.* 2010;12:327–341. Fig. 2.)

Table 735.7 | Dynamic Classification of Bone Dysplasias

I. EPIPHYSEAL DYSPLASIAS	
A. Epiphyseal hypoplasias	<ol style="list-style-type: none"> Failure of articular cartilage: spondyloepiphyseal dysplasia congenita and tarda Failure of ossification center: multiple epiphyseal dysplasia congenita and tarda
B. Epiphyseal hyperplasia	<ol style="list-style-type: none"> Excess of articular cartilage; dysplasia epiphysealis hemimelica
II. PHYSEAL DYSPLASIAS	
A. Cartilage hypoplasias	<ol style="list-style-type: none"> Failure of proliferating cartilage: achondroplasia congenita and tarda Failure of hypertrophic cartilage: metaphyseal dysostosis congenita and tarda
B. Cartilage hyperplasias	<ol style="list-style-type: none"> Excess of proliferating cartilage: hyperchondroplasia Excess of hypertrophic cartilage: enchondromatosis
III. METAPHYSEAL DYSPLASIAS	
A. Metaphyseal hypoplasias	<ol style="list-style-type: none"> Failure to form primary spongiosa: hypophosphatasia congenita and tarda Failure to absorb primary spongiosa: osteopetrosis congenita and tarda Failure to absorb secondary spongiosa: craniometaphyseal dysplasia congenita and tarda
B. Metaphyseal hyperplasias	<ol style="list-style-type: none"> Excessive spongiosa: multiple exostoses
IV. DIAPHYSEAL DYSPLASIAS	
A. Diaphyseal hypoplasias	<ol style="list-style-type: none"> Failure of periosteal bone formation: osteogenesis imperfecta congenita and tarda Failure of endosteal bone formation: idiopathic osteoporosis congenita and tarda
B. Diaphyseal hyperplasias	<ol style="list-style-type: none"> Excessive periosteal bone formation: progressive diaphyseal dysplasia Excessive endosteal bone formation: hyperphosphatasemia

From Rubin P. *Classification of bone dysplasias*. Chicago: Year Book Medical Publishers, 1964. p. 82.

Radiographic Features

Radiographic evaluation for a chondrodysplasia should include plain films of the entire skeleton. Efforts should be made to identify which bones and which parts of bones (i.e., epiphyses, metaphyses, diaphyses) are most affected (Figs. 735.3 and Fig. 735.4 and Table 735.7). If

possible, films taken at different ages should be examined because the radiographic changes evolve with time. Films taken before puberty are generally more informative because pubertal closure of the epiphyses obliterates many of the signs needed for a radiographic diagnosis. Prenatal diagnosis may also be possible with fetal ultrasound.

DIAGNOSIS

If an infant or child is short with disproportionate features, a diagnosis is established by matching the observed clinical picture (defined primarily from clinical, family, and gestational histories; physical examination; and radiographic evaluation) with clinical phenotypes of well-documented disorders. A number of reference texts and online databases provide information about the disorders and comprehensive lists of current references (<http://www.ncbi.nlm.nih.gov/books/NBK1116/>). Consultation with experts in medical genetics, orthopedics, endocrinology, or the bone dysplasia field is recommended.

Genetic testing for chondrodysplasias is very useful, especially for disorders in which recurrent pathogenic variants occur (typical achondroplasia has the same *FGFR3* pathogenic variant). Pathogenic variant testing for achondroplasia is available, although the diagnosis can be made clinically. The greatest utility for testing may be for prenatal diagnosis for couples where both parents have typical (*heterozygous*) achondroplasia. Their children are at a 25% risk of the much more severe *homozygous* achondroplasia (also known as *double dominant*), which can be detected by pathogenic variant analysis. Preimplantation genetic testing can be used to identify zygotes with two pathogenic variants in *FGFR3*. Another example of the utility of genetic testing is in disorders resulting from pathogenic variants in *DTDST*. These disorders are inherited in an autosomal recessive manner, and a limited number of mutant alleles have been found. If the pathogenic variants are identified in the patient, they should be detectable in the parents and potentially used for prenatal diagnosis. Pathogenic variant analysis is commercially available for many of the skeletal dysplasias and is increasingly used to confirm clinical diagnosis and for future pregnancy planning.

Many of the chondrodysplasias have distinct histologic changes of the skeletal growth plate. Sometimes, such tissues obtained at biopsy or discarded from a surgical procedure are helpful diagnostically. It is uncommon to make a diagnosis histologically if it was not already suspected on clinical or radiographic grounds.

MOLECULAR GENETICS OF SKELETAL DYSPLASIAS

A number of chondrodysplasia genes have been identified (see Table 735.2). They encode several categories of proteins, including cartilage matrix proteins, transmembrane receptors, ion transporters, and transcription factors. The number of identified gene loci is smaller than anticipated from the number of recognized clinical phenotypes. The majority of patients have disorders that map to fewer than 10 loci, and

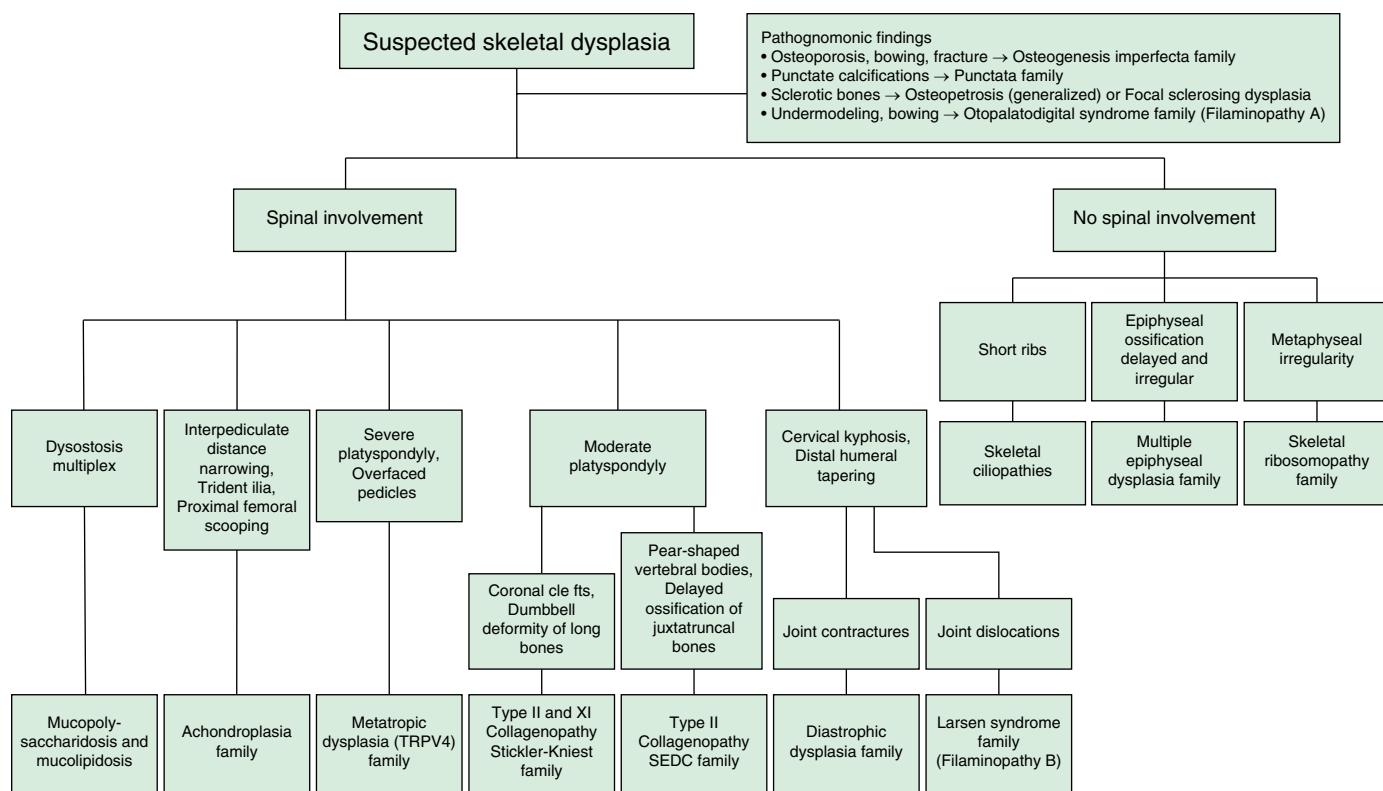


Fig. 735.4 Diagnostic algorithm for the major skeletal dysplasias. TRPV4, transient receptor potential vanilloid 4. (From Handa A, Grigelioniene G, Nishimura G: Skeletal dysplasia families: a stepwise approach to diagnosis. RadioGraphics 2023;43(5), Fig. 1.)

pathogenic variants at two loci (*COL2A1* and *FGFR3*) account for more than half of all cases. There may be a limited number of genes whose function is critical to skeletal development, especially linear bone growth, and pathogenic variants in these genes give rise to a wide range of chondrodysplasia clinical phenotypes. New genes harboring pathogenic variants that cause chondrodysplasias continue to be identified with advances in technology.

Pathogenic variants of *COL2A1* and *FGFR3* illustrate different genetic characteristics. *COL2A1* pathogenic variants are distributed throughout the gene, with few instances of recurrence in unrelated persons. In contrast, *FGFR3* pathogenic variants are restricted to a few locations within the gene, and the occurrence of new pathogenic variants at these same sites in unrelated persons is the rule. There is a strong correlation between clinical phenotype and pathogenic variant site for *FGFR3*, but not *COL2A1*.

PATHOPHYSIOLOGY

Chondrodysplasias are caused by pathogenic variants in genes that encode abnormal proteins and disrupt normal endochondral ossification, the biologic process responsible for the development and linear growth of the skeleton (see Fig. 735.1). These genetic variants act through different mechanisms. Most pathogenic variants involving cartilage matrix proteins cause disease when only one of the two copies (alleles) of the relevant gene is mutated. These pathogenic variants usually act through a *dominant negative mechanism* in which the protein products of the mutant allele interfere with the assembly and function of multimeric molecules that contain the protein products of both the normal and mutant alleles. The type II collagen molecule is a triple helix composed of three collagen chains, which are the products of the type II collagen gene *COL2A1*. When chains from both normal and mutant alleles are combined to form triple helices, most molecules contain at least one mutant chain. It is not known how many mutant chains are required to produce a dysfunctional molecule, but, depending on the pathogenic variant, it theoretically could be as few as one.

Pathogenic variants in the gene encoding type X collagen differ from the model above. They map to the region of the chain that is responsible for chain recognition; the chains must recognize each other before they can assemble into collagen molecules. Disease-causing variants are thought to disrupt this process. As a result, none of the mutant chains are incorporated into molecules. This mechanism is *haploinsufficiency* because the products of the mutant allele are functionally absent, and the normal allele is insufficient for normal function. Genetic variants involving ion transport genes also act through a *loss of function* of the transporters. Pathogenic variants of transmembrane receptors studied to date appear to act through a *gain of function*; the mutant receptors initiate signals in a constitutive manner independent of their normal ligands. A pathogenic variant in *FGFR3* is another example of a *gain of function* mechanism of disease. At baseline, *FGFR3* is a negative regulator of endochondral bone formation. If the pathogenic variant associated with achondroplasia is present in this gene, the clinical manifestations of this condition are caused by enhanced inhibition of endochondral bone formation and growth, independent of normal ligands.

TREATMENT

The first step is to establish the correct diagnosis. This allows one to provide a prognosis and to anticipate the medical and surgical problems associated with a particular disorder. Establishing a diagnosis helps to distinguish between lethal disorders and nonlethal disorders in a premature or newborn infant (see Tables 735.5 and 735.6). A poor prognosis for long-term survival might argue against initiating extreme lifesaving measures for thanatophoric dysplasia or achondrogenesis types Ib or II, whereas such measures may be indicated for infants with spondyloepiphyseal dysplasia congenita or diastrophic dysplasia, which have a good prognosis if the infant survives the newborn period.

Overall, management of patients with short stature skeletal dysplasias is directed at preventing and correcting skeletal deformities (spinal stenosis, kyphosis, scoliosis), treating nonskeletal complications (other anomalies, immunodeficiencies), providing genetic counseling, and

helping patients and families learn to cope. Each disorder has its own unique set of problems, and consequently, management must be tailored to each disorder.

There are a number of problems common to many chondrodysplasias for which general recommendations can be made. Children with most chondrodysplasias should avoid contact sports and other activities that cause injury or stress to joints. Good dietary habits should be established in childhood to prevent or minimize obesity in adulthood. Dental care should be started early to minimize the crowding and malalignment of teeth. Children and relatives should be given the opportunity to participate in support groups, such as the Little People of America (<http://www.lpaonline.org>) and Human Growth Foundation (<http://www.hgfound.org>).

Three controversial approaches have been used to increase bone length. Surgical limb lengthening has been employed for a few disorders. Its greatest success has been in achondroplasia in which nonskeletal tissues tend to be redundant and easily stretched. The procedure is usually performed during adolescence. Pharmacologic doses of human growth hormone comparable to those used to treat Turner syndrome have also been tried in several disorders; the results have been equivocal. Animal studies suggest that C-type natriuretic peptide (CNP) promotes linear bone growth in achondroplasia. One CNP analogue (vosoritide) is approved to increase height in children with achondroplasia (≥ 5 years old) before the growth plates are closed. Palovarotene is undergoing clinical trials for fibrodysplasia ossificans and resveratrol for pseudoachondroplasia. Enzyme replacement therapy is available for hypophosphatasia and Morquio A syndrome. Many new therapies are based on the gene or pathway involved in the specific disease (see Chapters 736–742). [Clinicaltrials.gov](#) is a resource to access information about these and all other clinical trials.

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Chapter 736

Disorders Involving Cartilage Matrix Proteins

Daniah Albokhari and Julie E. Hoover-Fong

Disorders of cartilage matrix proteins resulting in bone and joint disorders can be classified according to the defective proteins: collagens (types 2, 9, 10, 11) and the noncollagenous proteins COMP (cartilage oligomeric matrix protein), matrilin-3, and aggrecan. The clinical phenotypes and clinical severity differ between and within the groups, especially the spondyloepiphyseal dysplasia (SED) group, which is made up largely of type collagenopathies (see also Table 735.1).

TYPE 2 COLLAGENOPATHIES

The term *spondyloepiphyseal dysplasia* refers to a heterogeneous group of disorders characterized by shortening of the trunk and, to a lesser extent, the limbs. Severity ranges from most severe and often lethal perinatally, such as achondrogenesis type II, hypochondrogenesis, and platyspondyl dysplasia, Torrance type, to severe/moderately severe neonatal presentation, such as Kniest dysplasia (which is apparent at birth and usually nonlethal) and SED congenita, to mild SED with premature-onset arthrosis (which might not be detected until adolescence or later) (Table 736.1). The radiographic hallmarks are abnormal development of the vertebral bodies and of

epiphyses, the extent of which corresponds with clinical severity. Most of the SEDs result from heterozygous pathogenic variants of *COL2A1* and are autosomal dominant disorders. The pathogenic variants are dispersed throughout the gene with imperfect correlation between the variant location and resultant clinical phenotype. Molecular testing/confirmation is readily available commercially. Prenatal diagnosis is possible if the pathogenic variant is known.

Lethal Spondyloepiphyseal Dysplasias

Achondrogenesis type II is characterized by severe shortening of the neck and trunk and especially the limbs, and by a large, soft head. Fetal hydrops and prematurity are common, and infants are stillborn or die shortly after birth. Hypochondrogenesis refers to a clinical phenotype intermediate between achondrogenesis type II and SED congenita. It is typically lethal in the newborn period. Platyspondyl dysplasia, Torrance type is characterized by disproportionate short stature, short limbs, and coarse facial features. The majority of infants die at or shortly after birth.

The severity of radiographic changes correlates with clinical severity. These conditions manifest short, broad tubular bones with cupped metaphyses. The cranial bones are not well mineralized, and the vertebral bodies are poorly ossified in the entire spine in achondrogenesis type II, and in the cervical and sacral spine in hypochondrogenesis. In both conditions, the pelvic bones are hypoplastic, and the pedicles are ossified. In Torrance type, the platyspondyly is strikingly severe, with iliac hypoplasia, short sacrosciatic notches, and preserved ossification of the pubic bones. The three types can be detected prenatally and confirmed by molecular testing.

KNIEST DYSPLASIA

The Kniest dysplasia variant of SED manifests at birth with a short trunk and limbs associated with a flat face, prominent eyes, enlarged joints, cleft palate, and clubfoot (Fig. 736.1). Radiographs show vertebral defects and short tubular bones with epiphyseal irregularities and metaphyseal enlargement that gives rise to a dumbbell appearance.

Motor development is often delayed because of the joint deformities, although intelligence is normal. Hearing loss and myopia commonly develop during childhood, and retinal detachment is a common complication. Joint enlargement progresses during childhood and becomes painful. It is accompanied by flexion contractures and muscle atrophy, which may be incapacitating by adolescence.

Spondyloepiphyseal Dysplasia Congenita

The phenotype of this group, SED congenita, is apparent at birth. The hands and feet are usually normal. Craniofacial features may present, including malar hypoplasia, hypertelorism, and cleft palate. The neck is short, and the chest is barrel shaped (Fig. 736.2). Kyphosis and exaggeration of the normal lumbar lordosis are common. The proximal segments of the limbs are shorter than the hands and feet, which often appear normal. Some infants have clubfoot and/or exhibit hypotonia.

Skeletal radiographs of the newborn reveal short tubular bones, delayed ossification of vertebral bodies, and proximal limb bone epiphyses (Fig. 736.3). Hypoplasia of the odontoid process, a short, square pelvis with a poorly ossified symphysis pubis, and mild irregularity of metaphyses are apparent.

Infants usually have normal developmental milestones with a waddling gait typically appearing in early childhood. Childhood complications include respiratory compromise from tracheomalacia, spinal deformities, and spinal cord compression because of cervicomедullary instability. The disproportion and shortening become progressively worse with age, and adult heights range from 95–128 cm. Myopia is typical; adults are predisposed to retinal detachment. Precocious osteoarthritis (OA) occurs in early adulthood and requires surgical joint replacement.

Table 736.1 Collagen Disorders

DISORDER	INHERITANCE	GENE
TYPE 2 COLLAGEN DISORDERS		
Achondrogenesis (formerly type 2, type Langer-Saldino)	AD	COL2A1
Hypochondrogenesis	AD	COL2A1
Platyspondylic dysplasia, type Torrance	AD	COL2A1
Spondyloepiphyseal dysplasia congenita	AD, AR	COL2A1
Spondyloepimetaphyseal dysplasia	AD	COL2A1
Kniest dysplasia	AD	COL2A1
Spondyloperipheral dysplasia	AD	COL2A1
SED with metatarsal shortening	AD	COL2A1
Stickler syndrome	AD	COL2A1
Dysplasia of the proximal femoral epiphyses	AD	COL2A1
TYPE XI COLLAGEN DISORDERS		
Stickler syndrome	AD, MOS	COL11A1
Marshall syndrome	AS	COL11A1
Stickler syndrome (nonocular type)	AD	COL11A2
Fibrochondrogenesis	AR, AD	COL11A1
Fibrochondrogenesis	AR, AD	COL11A2
Otospondylomegaepiphyseal dysplasia	AR	COL11A2
Otospondylomegaepiphyseal dysplasia	AD	COL11A2

Data from Unger S, Ferreira CR, Mortier GR, et al. Nosology of genetic skeletal disorders: 2023 revision. *Am J Med Genet*. 2023;191A:1164-1209 (Table 1, Group 2 and 3, pp 1166-1167).

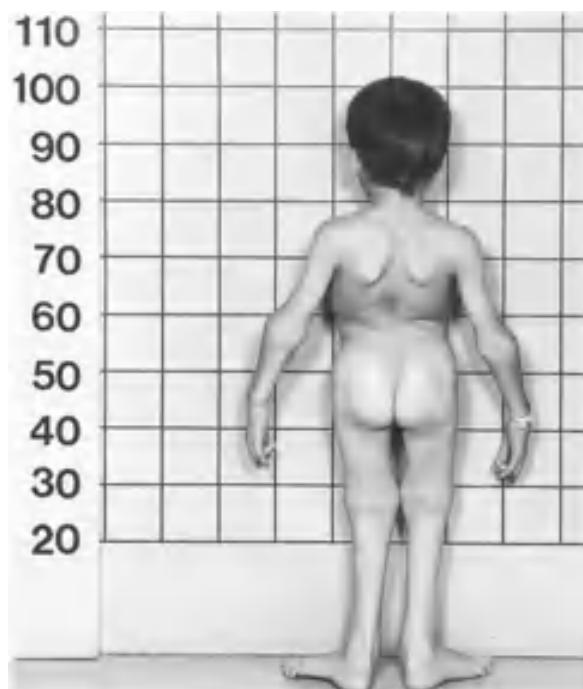


Fig. 736.1 Patient with Kniest dysplasia. The trunk is short, the epiphyses are broad, and there is contracture of the fingers. (From Traboulsi El. *Skeletal and connective tissue disorders with anterior segment manifestations*. In Krachmer JH, Mannis MJ, Holland EJ, eds. *Cornea*, 3rd ed. Philadelphia: Elsevier; 2011. Fig. 60.9.)

Mild Spondyloepiphyseal Dysplasia with Premature-Onset Arthritis

Late-onset SED is a mild clinical phenotype characterized by slightly short stature, progressive joint pain, and diminished range of movement, associated with mild epiphyseal and vertebral abnormalities on radiographs. It is typically detected during childhood or adolescence but can go unrecognized until adulthood when precocious OA appears. The vision and hearing are usually normal. This designation is nosologically distinct from SED tarda, which is clinically similar but results from pathogenic variant of the X-linked gene *SEDL* (*TRAPPC2*).

Stickler Syndrome/Dysplasia (Hereditary Progressive Arthro-Ophthalmopathy)

Short stature is not a feature of Stickler dysplasia. This condition resembles SED because of its joint and eye manifestations. Pathogenic variants of genes encoding type II (*COL2A1*), type XI (*COL11A1*, *COL11A2*), and type IX (*COL9A1*, *COL9A2*, *COL9A3*) collagens have been identified in Stickler-like disorders. Stickler dysplasia is often identified in the newborn because of cleft palate and micrognathia (*Pierre Robin* anomaly; see Chapter 357). Of patients with Stickler syndrome, 25% have *Pierre Robin* anomaly, and 18% of patients with *Pierre Robin* anomaly have Stickler syndrome. Children with Stickler syndrome are often identified in craniofacial clinics. Infants typically have severe myopia and additional ophthalmologic complications, including cataracts, glaucoma, and choroidoretinal and vitreous degeneration, with retinal detachment common during childhood requiring multiple surgical interventions (Fig. 736.4). Special attention must be given to eye complications even in childhood to preserve vision for these individuals. Hearing loss is a common feature that arises during adolescence. Sensorineural hearing loss is the most common form; however, conductive hearing loss may also be seen. Osteoarticular manifestations include joint hypermobility (especially hip), which resolves in adulthood, metaphyseal broadening of the femoral neck, hypoplastic iliac wings, Schmorl nodes, muscle hypotonia, metaphyseal-epiphyseal dysplasia, precocious progressive OA of the spine and peripheral joints (which may require hip replacement surgery before age 30 years), and decreased bone density. Similar manifestations may be seen in other diseases with pathogenic variants in type II and XI collagen genes (Table 736.2).

PSEUDOACHONDROPLASIA AND MULTIPLE EPIPHYSEAL DYSPLASIA

Pseudoachondroplasia and the most common form of multiple epiphyseal dysplasia (MED) are two distinct phenotypes that are grouped together because they result from pathogenic variants of the gene encoding *COMP*. The pathogenic variants are heterozygous in both, and they are autosomal dominant traits. The clinical phenotypes are restricted to musculoskeletal tissues. Newborns with pseudoachondroplasia are average in size and appearance. Gait abnormalities and short stature mainly affect the limbs and become apparent in late infancy. Short stature becomes marked as the child grows and is associated with generalized joint laxity (Fig. 736.5). The hands are short, broad, and deviated in an ulnar direction; the forearms are bowed. Developmental milestones and intelligence are usually normal. Lumbar lordosis and deformities of the knee develop during childhood; the latter often requires surgical correction. Pain is common in weight-bearing joints during childhood and adolescence, and OA develops late in the second decade of life, which may require hip replacement by mid-30s. Adult height ranges from 105-128 cm. Skeletal radiographs show distinctive abnormalities of vertebral bodies and of both epiphyses and metaphyses of tubular bones (Fig. 736.6).

The MED phenotype has skeletal abnormalities that predominantly affect the epiphyses as noted on radiographs. Two forms, the severe Fairbank type and the mild Ribbing type, are no longer used in classification. Because of overlap in clinical features, and because *COMP* pathogenic variants are found in both types, they are now considered part of a clinical spectrum. The more severe clinical

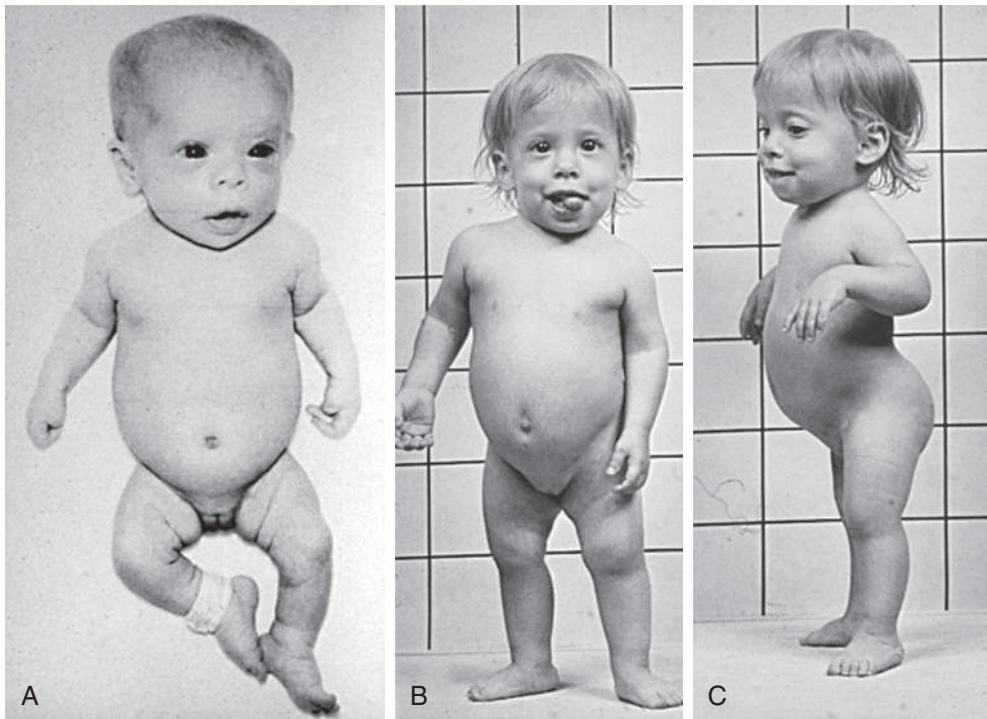


Fig. 736.2 Spondyloepiphyseal dysplasia congenita is shown in infancy (A) and early childhood (B, C). Note the short extremities, relatively normal hands, flat facies, and exaggerated lordosis.



Fig. 736.3 Spondyloepiphyseal dysplasia. Platyspondyly, delayed epiphyseal ossification (especially femoral heads), dens hypoplasia. (From Campeau P, Schlesinger AE. *Skeletal dysplasias*. [Updated 2017 Jan 30]. In: De Groot LJ, Chrousos G, Dungan K, et al., eds. *Endotext* [internet]. South Dartmouth, MA, 2000, MDText.com, Inc. Fig. 5. Available from <https://www.ncbi.nlm.nih.gov/books/NBK279130/>.)

phenotype of MED has its onset during childhood, with mild short-limbed short stature, pain in weight-bearing joints, and a waddling gait. Radiographs show delayed and irregular ossification of epiphyses. A typical finding is the double-layered patella (pathognomonic). In more mildly affected patients, the disorder might not be recognized until adolescence or adulthood. Radiographic changes may be limited to the capital femoral epiphyses. In the latter case, mild MED must be distinguished from bilateral Legg-Calvé-Perthes disease (see Chapter 719.3). Precocious OA of hips and knees is the major complication in adults with MED. Adult heights range from 136–151 cm.

There are families with clinical and radiographic manifestations of MED that are not caused by pathogenic variants of COMP. Pathogenic variants in the genes encoding all three of the type IX collagen chains have been

reported. It has been suggested that COMP and type IX collagen interact functionally in cartilage matrix, thus explaining why pathogenic variants of different genes produce similar pictures. Pathogenic variants of the genes coding for another cartilage matrix protein, matrilin-3 (*MATN3*), and the diastrophic dysplasia sulfate transporter (*SLC26A*) have also been found in patients with autosomal dominant and recessive MED, respectively. For familial cases of pseudoachondroplasia and MED resulting from pathogenic variant in COMP, prenatal diagnosis is available.

Spondyloepimetaphyseal dysplasia, Borochowitz-Cormier-Daire type

Spondyloepimetaphyseal dysplasia, Borochowitz-Cormier-Daire type is a rare more severe spondylo-epi-metaphyseal dysplasia (SEMD)-like phenotype characterized by short-limb dwarfism with spinal,

Daughter



Mother



Fig. 736.4 Face and profile of a mother and daughter with Stickler syndrome type I. Note in the daughter the flat nasal bridge, the mild epicanthal folds, and discrete micrognathia. At first sight, the mother shows no clear facial characteristics of Stickler syndrome. (From Bajens LWJ, De Leenheer EMR, Weekamp HH, et al. Stickler syndrome type I and Stapes ankylosis. *Int J Pediatr Otorhinolaryngol*. 2004;68:1573–1580. Fig. 2.)

Table 736.2 Other Genetic Diseases Associated with Pathogenic Variants in Type II and Type XI Collagen Genes, with Clinical Presentations Similar to That of Stickler Syndrome

PHENOTYPES ASSOCIATED WITH COL2A1 PATHOGENIC VARIANTS

Achondrogenesis type II
Hypochondrogenesis
Spondyloepiphyseal dysplasia congenita
Spondyloepimetaphyseal dysplasia, Strudwick type
Kniest dysplasia
Platyspondylic skeletal dysplasia, Torrance type
Spondyloperipheral dysplasia
Czech dysplasia
Spondyloepiphyseal dysplasia, Stanescu type
Dysplasia with altered vertebral contours
Some of the juvenile joint diseases

PHENOTYPES ASSOCIATED WITH COL11A1 PATHOGENIC VARIANTS

Marshall syndrome
Fibrochondrogenesis 1
Autosomal dominant deafness

PHENOTYPES ASSOCIATED WITH COL11A2 PATHOGENIC VARIANTS

Otospondylometaphyseal dysplasia
Weissenbacher-Zweymüller syndrome
Fibrochondrogenesis 2
Some cases of isolated sensorineural deafness

Table adapted from Couchouron T, Masson C. Early-onset progressive osteoarthritis with hereditary progressive ophthalmology or Stickler syndrome. *Joint Bone Spine*. 2011;78:45–49. [Table 1](#), p. 48; with additional data from Mortier GR, Cohn DH, Cormier-Daire V, et al. Nosology and classification of genetic skeletal disorders: 2019 revision. *Am J Med Genet A*. 2019;179(12):2393–2419.

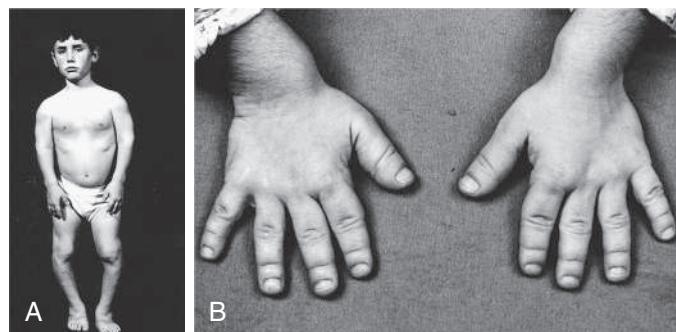


Fig. 736.5 Pseudoachondroplasia in an adolescent male. A, The facets and head circumference are normal. There is shortening of all extremities and bowing of the lower extremities. B, Photograph of hands, demonstrating short stubby fingers.

epiphyseal, and metaphyseal abnormalities. There are only three families described in the literature caused by autosomal recessive pathogenic variant in the gene encoding matrilin-3 (*MATN3*). Radiographic examination showed flat, ovoid vertebral bodies, short with a stocky appearance, long tubular bones, wide metaphysis with lateral spurs, irregular epiphysis of knee, unossified proximal femur epiphysis, squaring of pelvis, and narrow greater sciatic notch.

SCHMID METAPHYSEAL DYSPLASIA

Schmid metaphyseal dysplasia is one of several chondrodysplasias in which metaphyseal abnormalities dominate the radiographic features. It typically manifests in early childhood with mild short stature, bowing of the legs, and a waddling gait ([Fig. 736.7](#)). Joints, such as the wrist, may be enlarged. Radiographs show flaring and irregular mineralization of the metaphyses of tubular bones of the proximal

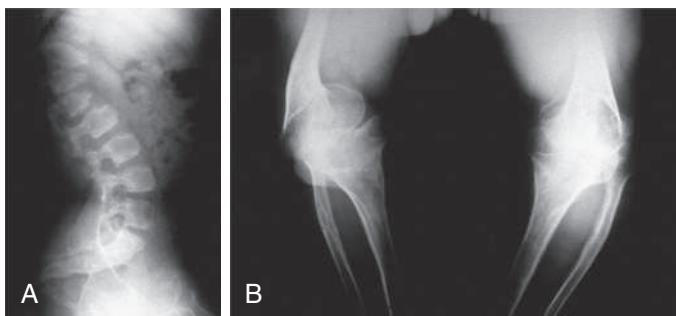


Fig. 736.6 A, Lateral thoracolumbar spine radiograph of a patient with pseudoachondroplasia showing central protrusion (tonguing) of the anterior aspect of upper lumbar and lower thoracic vertebrae. Note reduced vertebral body heights (platyspondyly) and secondary lordosis. B, Lower-extremity radiograph of a patient with pseudoachondroplasia showing large metaphyses, poorly formed epiphyses, and marked bowing of the long bones.



Fig. 736.7 Female patient with metaphyseal dysplasia, type Schmid. The facies are normal, and the stature is mildly reduced. Mild tibia vara is present.

limbs (Fig. 736.8). Coxa vara is usually present and can require surgical correction. Short stature becomes more evident with age and affects the lower extremities more than the upper extremities. Overall, manifestations are limited to the skeleton. Schmid metaphyseal chondrodysplasia is caused by heterozygous pathogenic variants



Fig. 736.8 Radiograph of lower extremities in Schmid metaphyseal dysplasia showing short tubular bones and metaphyseal flaring and irregularities, abnormal capital femoral epiphyses, and femoral necks. The epiphyses are normal. Coxa vara is present.

in the gene encoding type X collagen (*COL10A1*) as an autosomal dominant condition. The distribution of type X collagen is restricted to the region of growing bone in which cartilage is converted into bone. This might explain why radiographic changes are confined to the metaphyses.

Aggrecan-Related Spondyloepiphyseal Dysplasias

Pathogenic variants of aggrecan have been detected in three SED-like conditions. SED-Kimberley is relatively mild, with short stature, stocky build, and early-onset OA of weight-bearing joints. Autosomal dominant pathogenic variants are etiologic. Autosomal recessive pathogenic variants cause a more severe and generalized clinical phenotype, **spondyloepimetaphyseal dysplasia-aggrecan type**. Radiographic changes include irregular epiphyses and widened metaphyses. A mild condition, **familial osteochondritis dissecans**, is characterized by multiple osteochondritic lesions (separation of cartilage and subchondral bone from the surrounding tissue and primarily affecting the knee, ankle, and elbow joints) in knees and/or hips and/or elbows, disproportionate short stature, and early-onset OA. Autosomal dominant pathogenic variants have been found in familial cases.

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Chapter 737

Disorders Involving Transmembrane Receptors

Daniah Albokhari and Julie E. Hoover-Fong

Heterozygous pathogenic variants of genes encoding *FGFR3* (fibroblast growth factor receptor 3) and *PTHR1* (parathyroid hormone-1 receptor) result in disorders involving transmembrane receptors. The pathogenic variants cause the receptors to become activated in the absence of physiologic ligands, which accentuates normal receptor function of negatively regulating bone growth. The pathogenic variants act by gain of negative function. In the *FGFR3* pathogenic variant group, in which the clinical phenotypes range from severe to mild, the severity appears to correlate with the extent to which the receptor is activated. *PTHR1* and especially *FGFR3* pathogenic variants tend to recur in unrelated individuals (Table 737.1; see also Table 735.1).

FGFR3 CHONDRODYSPLASIA GROUP

The achondroplasia group represents a substantial percentage of patients with chondrodysplasias and contains thanatophoric dysplasia (TD), the most common lethal chondrodysplasia, with a birth prevalence of 1 in 35,000 births and achondroplasia, the most common non-lethal chondrodysplasia, with a birth prevalence of 1 in 15,000–25,000 births. Also in this group are severe achondroplasia with developmental delay and acanthosis nigricans (SADDAN), hypochondroplasia, and camptodactyly, tall stature, and hearing loss syndrome (CATSHL). All five have pathogenic variants in a small number of locations in the *FGFR3* gene. There is a strong correlation between the pathogenic variant site and the clinical phenotype.

Thanatophoric Dysplasia

TD manifests before or at birth. In the former situation, ultrasonographic examination in mid-gestation or later reveals a large head and very short limbs; the pregnancy is often accompanied by

polyhydramnios and premature delivery. Very short limbs, short neck, long narrow thorax, and large head with midfacial hypoplasia dominate the clinical phenotype at birth (Fig. 737.1). The cloverleaf skull deformity known as **kleeblattschädel** is sometimes found. If the affected fetus survives pregnancy, the newborn will have severe respiratory distress because of the small thorax. Although this distress can be treated by intense respiratory care, the long-term prognosis is poor.

Skeletal radiographs distinguish two slightly different forms called TD I and TD II. In the more common TD I, radiographs show large calvarium with a small cranial base, marked thinning and flattening of vertebral bodies (platyspondyly) visualized best on lateral view, very short ribs, severe hypoplasia of pelvic bones, and very short and bowed tubular bones with flared metaphyses (Fig. 737.2). The femurs are curved and shaped like a telephone receiver. TD II differs mainly in that there are longer and straighter femurs.

The TD II clinical phenotype is associated with pathogenic variants that map to codon 650 of *FGFR3*, causing the substitution of a lysine with glutamic acid. This activates the tyrosine kinase activity of a receptor that transmits signals to intracellular pathways. The pathogenic variant of the same lysine 650 to methionine is also associated with a clinical phenotype intermediate between TD and achondroplasia, referred to as **SADDAN (severe achondroplasia with developmental delay and acanthosis nigricans)**, where affected cases often do not require ventilatory support and survive beyond infancy. Pathogenic variants of the TD I phenotype mainly map to two regions in the extracellular domain of the receptor, where they substitute cysteine residues for other amino acids. Free cysteine residues are thought to form disulfide bonds promoting dimerization of receptor molecules, leading to activation and signal transmission. TD I and TD II typically present as new pathogenic variants in offspring born to unaffected, average stature parents. The recurrence risk is low. Because the variant codons in TD are pathogenic for unknown reasons and because of the theoretical risk of germ cell mosaicism, parents are offered prenatal diagnosis for subsequent pregnancies.

Achondroplasia

Achondroplasia is the prototype chondrodysplasia. It typically manifests at birth with short limbs, a long narrow trunk, and a large head with midfacial hypoplasia and prominent forehead (Fig. 737.3). The limb shortening is greatest in the proximal segments (rhizomelia), and the fingers often display a trident configuration. Most joints are hyperextensible, but extension is restricted at the elbow. A thoracolumbar gibbus is typically found in newborns but improves as they start walking with no intervention in 90% of the cases. Birth length may be slightly less than normal but often plots within the low-normal range.

Diagnosis

Skeletal radiographs confirm the diagnosis (Fig. 737.4; see also Fig. 737.3). The calvarial bones are large, whereas the cranial base and facial bones are small. The vertebral pedicles are short throughout the spine as noted on a lateral radiograph. The interpedicular distance, which normally increases from the first to the fifth lumbar vertebra, decreases in achondroplasia. The iliac bones are short and round, and the acetabular roofs are flat. The tubular bones are short with mildly irregular and flared metaphyses. The fibula is disproportionately long compared with the tibia, which is often bowed, causing genu varum.

Clinical Manifestations

Infants usually exhibit delayed motor milestones, often not walking alone until 18–24 months. This is because of hypotonia and mechanical difficulty balancing the large head on a normal-sized trunk and short extremities. Intelligence is normal unless central nervous system complications develop. As the child begins to walk, the gibbus usually gives way to an exaggerated lumbar lordosis.

Infants and children with achondroplasia progressively fall below normal standards for length and height. They can be plotted against standards established for achondroplasia. Adult heights typically are 118–145 cm for men and 112–136 cm for women. C-type natriuretic

Table 737.1 FGFR3 Chondrodysplasia Group

GROUP/NAME OF DISORDER	INHERITANCE	OMIM	GENE
Thanatophoric dysplasia type I (TD I)	AD	187600	<i>FGFR3</i>
Thanatophoric dysplasia type II (TD II)	AD	187601	<i>FGFR3</i>
Severe achondroplasia with developmental delay and acanthosis nigricans (SADDAN)	AD	616482	<i>FGFR3</i>
Achondroplasia	AD	100800	<i>FGFR3</i>
Hypochondroplasia	AD	146000	<i>FGFR3</i>
Camptodactyly, tall stature, and hearing loss syndrome (CATSHL)	AD	610474	<i>FGFR3</i>

Please also refer to group 33 from Mortier et al nosology for craniosynostoses syndromes linked to FGFR3 pathogenic variants, as well as LADD syndrome in group 41 for another FGFR3-related phenotype.

OMIM, Online Mendelian Inheritance in Man (omim.org).

From Campeau P, Schlesinger AE: Skeletal dysplasias. [Updated 2017 Jan 30]. In: De Groot LJ, Chrousos G, Dungan K, et al. (eds). *Endotext [internet]*. South Dartmouth, MA, 2000, MDText.com, Inc. Available from <https://www.ncbi.nlm.nih.gov/books/NBK279130/>.



Fig. 737.1 Identical twins with type I thanatophoric dysplasia. Disproportionately large head, bell-shaped chest, and micromelia. (From Gilbert-Barness E, Kapur RP, Oligny LL, Siebert JR, eds. *Potter's Pathology of the Fetus, Infant and Child*, 2nd ed. Philadelphia: Elsevier, 2007. Fig. 20-47.)

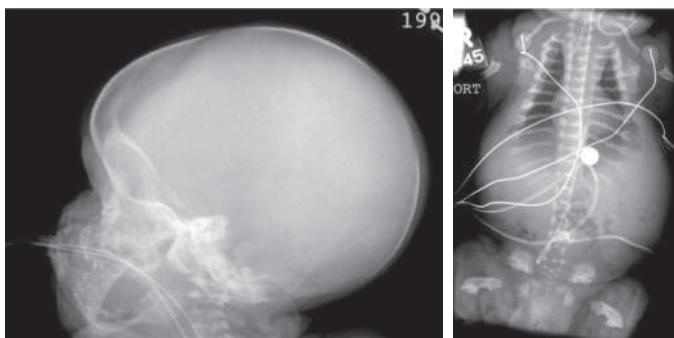


Fig. 737.2 Thanatophoric dysplasia type I. Severe platyspondyly, very short ribs, narrow thorax, short broad pelvis, large skull, very short and bent long bones. (From Campeau P, Schlesinger AE. *Skeletal dysplasias*. [Updated 2017 Jan 30]. In De Groot LJ, Chrousos G, Dungan K, et al., eds. *Endotext* [internet]. South Dartmouth, MA, 2000, MDText.com, Inc., Fig. 1. Available from <https://www.ncbi.nlm.nih.gov/books/NBK279130/>.)

peptide analogue (vosoritide), administered as a daily subcutaneous injection is the first approved treatment for children ≥ 5 years of age with achondroplasia; treatment with vosoritide produced an increase of annual growth velocity with no significant side effect. In addition, vosoritide maintains this annual growth velocity up to 2 years along with an improvement in body segment proportion. Clinical trials are underway to study other compounds such as soluble FGFR3 decoy receptors, and tyrosine kinase inhibitors, which may restore bone growth in achondroplasia based on studies in animal models. Other possible future treatments of achondroplasia include fibroblast growth factor aptamers and meclizine, which showed improvement of the skeletal phenotype of the mutant mice. Surgical limb lengthening and human growth hormone treatment have been used to increase height; however, both are controversial.

Virtually all infants and children with achondroplasia have large heads, although only a fraction have true hydrocephalus. Head circumference should be carefully monitored using standards developed for achondroplasia, as should neurologic function in general. The spinal canal is stenotic, and spinal cord compression can occur at the foramen magnum and in the lumbar spine. The former usually occurs in infants and small children and may be associated with hypotonia, failure to



Fig. 737.3 Achondroplasia phenotype at different ages. A, Infant with achondroplasia with macrocephaly, frontal bossing, midface hypoplasia, small chest, rhizomelic shortening of all the limbs, redundant skinfolds, and extreme joint laxity. Note the trident hand with short fingers and abducted hips. B, Typical radiographic findings from a child with achondroplasia. All of the tubular bones are short, but the fibula is relatively long compared with the tibia. There is protrusion of the epiphysis into the metaphysis of the distal femur, creating the chevron deformity, and—to a lesser extent—of the proximal tibia. The iliac bones are rounded, the acetabular roof is horizontal, and the sacrosciatic notches are small. C, A 3-yr-old with achondroplasia with the typical features shown in (A). Note that the redundant skinfolds are no longer present and that joint laxity has improved. Rhizomelic shortening of the extremities is more pronounced and accompanied by tibial bowing. (From Horton WA, Hall JG, Hecht JT. Achondroplasia. *Lancet*. 2007;370:162–172.)

thrive, quadriplegia, central and obstructive apnea, and sudden death. Surgical correction may be required for severe stenosis. Lumbar spinal stenosis usually does not occur until early adulthood. Symptoms include paresthesias, numbness, and claudication in the legs. Loss of bladder and bowel control may be late complications. Bowing of the legs is common in patients with achondroplasia and might need to be corrected surgically. Other common problems include dental crowding, articulation difficulties, obesity, and frequent episodes of otitis media, which can contribute to hearing loss.

Genetics

All patients with typical achondroplasia have pathogenic variants at *FGFR3* codon 380. This pathogenic variant is located in the transmembrane domain of the receptor and is thought to stabilize receptor dimers that enhance receptor signals, the consequences of which inhibit linear bone growth. Achondroplasia behaves as an autosomal dominant condition; most cases arise from a new pathogenic variant to average stature parents.

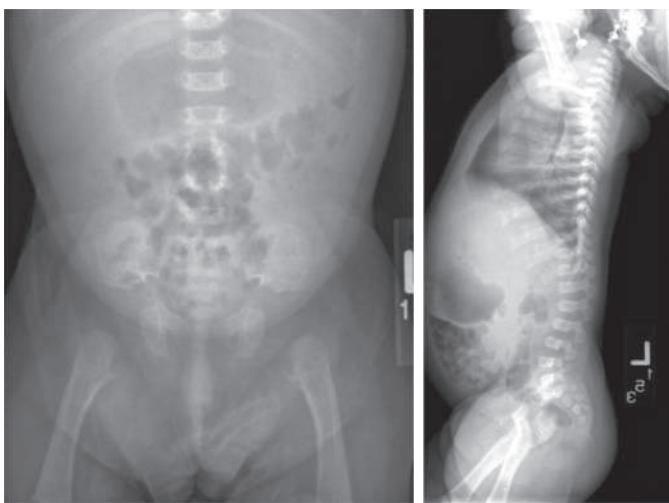


Fig. 737.4 Achondroplasia. Small rounded iliac bones, horizontal acetabula, decreasing interpediculate distance, normal vertebral body height, short ribs. (From Campeau P, Schlesinger AE. *Skeletal dysplasias*. [Updated 2017 Jan 30]. In De Groot LJ, Chrousos G, Dungan K, et al., eds. *Endotext* [internet]. South Dartmouth, MA, 2000, MDText.com, Inc., Fig. 2. Available from <https://www.ncbi.nlm.nih.gov/books/NBK279130/>.)

Because of the high frequency of achondroplasia among short stature skeletal dysplasias, it is relatively common for adults with achondroplasia to marry. Such couples have a 50% risk of transmitting their condition, heterozygous achondroplasia, to each offspring, as well as a 25% risk of **homozygous achondroplasia**. The latter condition exhibits intermediate severity between TD and heterozygous achondroplasia and is usually lethal in the newborn period and is often referred to as “double dominant” inheritance. Prenatal diagnosis is available and has been used to diagnose homozygous achondroplasia. Preimplantation genetic testing can be used to identify double dominant pathogenic variants.

Hypochondroplasia

Hypochondroplasia resembles achondroplasia but is milder. Usually, it is not apparent until childhood, when mild short stature affecting the limbs becomes evident. Children have a stocky build, disproportionately short extremities, and slight frontal bossing of the head. Learning disabilities may be more common in this condition. Radiographic changes are mild and consistent with the mild achondroplastic phenotype. Complications are rare; in some patients, the condition is never diagnosed. Adult heights range from 131–154.5 cm for men and 124–138 cm for women. An *FGFR3* pathogenic variant at codon 540 is the most pathogenic variant found in patients with more severe hypochondroplasia. Genetic heterogeneity exists in hypochondroplasia; that is, *SHOX* pathogenic variants are associated with a very similar clinical phenotype. Recombinant growth hormone therapy may enhance growth and improve body disproportion but is still considered controversial with limited evidence of increased final adult height.

JANSEN METAPHYSEAL DYSPLASIA

Jansen metaphyseal chondrodysplasia is a rare, dominantly inherited chondrodysplasia characterized by severe shortening of limbs associated with an unusual facial appearance (see Chapter 735). Sometimes it is accompanied by clubfoot and **hypercalcemia** with serum calcium values of 13–15 mg/dL. At birth, a diagnosis can be made from these clinical findings, and radiographs that show short tubular bones with characteristic metaphyseal abnormalities that include flaring, irregular mineralization, fragmentation, and widening of the physeal space. The epiphyses are normal. The joints become enlarged and limited in mobility with age. Flexion contractures develop at the knees and hips, producing a bent-over posture. The spine can also be deformed by

irregular growth of vertebrae. Intelligence is normal, although there may be hearing loss.

Jansen metaphyseal chondrodysplasia is caused by activating pathogenic variants of *PTHR1*. This G-protein-coupled transmembrane receptor serves as a receptor for both parathyroid hormone and parathyroid hormone-related peptide. Signaling through this receptor serves as a brake on the terminal differentiation of cartilage cells at a critical step in bone growth. Because the pathogenic variants activate the receptor, they enhance the braking effect and thereby slow bone growth. In contrast, loss-of-function pathogenic variants of *PTHR1* are observed in Blomstrand chondrodysplasia, whose clinical features are the mirror image of Jansen metaphyseal chondrodysplasia.

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Chapter 738

Disorders Involving Ion Transporters

Daniah Albokhari and Julie E. Hoover-Fong

Five genes related to ion transporters have been reported to be involved in skeletal dysplasia conditions, including the *SLC39A13* gene causing Ehlers-Danlos syndrome, spondylodysplastic type, the *SLCO2A1* gene causing hypertrophic osteoarthropathy (OA), the *SLC10A7* gene causing multiple joint dislocations with amelogenesis imperfecta, and the *SLC34A3* gene causing hypophosphatemic rickets with hypercalciuria (HHRH). This chapter will focus on pathogenic variants in the sulfate transporter gene (*SLC26A2*), also known as **diastrophic dysplasia sulfate transporter (DTDST)**, which is the most common ion transporter gene causing sulphation disorders skeletal dysplasia. It encompasses a spectrum of both lethal and nonlethal chondrodysplasia, including, in order of decreasing severity, achondrogenesis type 1B, atelosteogenesis type II, diastrophic dysplasia, and a rare recessive form of multiple epiphyseal dysplasia (rMED). The gene product sulfate transporter is important to uptake sulfate ions into cells and is important for cartilage cells that add sulfate moieties to newly synthesized proteoglycans destined for cartilage extracellular matrix. Matrix proteoglycans are responsible for many of the properties of cartilage that allow it to serve as a template for skeletal development. The clinical manifestations result from defective sulfation of cartilage proteoglycans (see also Table 735.1).

A number of pathogenic alleles have been found for the *DTDST* gene; they variably disturb transporter function. The disorders are recessive traits requiring the presence of bi-allelic pathogenic variants. The phenotype is determined by the combination of abnormal alleles with some alleles present in more than one disorder.

Achondrogenesis Type 1B and Atelosteogenesis Type 2

Achondrogenesis type 1B and atelosteogenesis type 2 are rare recessive lethal chondrodysplasias. The most serious is achondrogenesis type 1B, which demonstrates a severe lack of skeletal development usually detected in utero or after a miscarriage. The limbs are extremely short, the head is soft, the thorax is narrow, and the abdomen protuberant. Skeletal radiographs show poor to missing ossification of skull bones, vertebral bodies, fibulas, and ankle bones. The pelvis is hypoplastic, and the ribs are short and slightly thin. The femurs are short and exhibit a trapezoid shape with irregular metaphyses.



Fig. 738.1 Child with diastrophic dysplasia. The extremities are dramatically shortened (top). Clubfoot is commonly observed (middle left). The fingers are short, especially the index finger; the thumb characteristically is proximally placed and has a hitchhiker appearance (middle right). The upper helix of the ears becomes swollen 3-4 wk postnatally (lower left), and this inflammation spontaneously resolves, leaving a cauliflower deformity of the pinnae (lower right).

Infants with atelosteogenesis type II are stillborn or die soon after birth; prematurity is common. They exhibit very short limbs, especially the proximal segments with normal size head and midface hypoplasia. Clubfoot and dislocations of the elbows and knees may be detected. Hypoplasia of vertebral bodies, especially in the cervical and lumbar spine, and hypoplastic ilia with flat acetabulum are found on radiographs. The femora and humeri are hypoplastic and display a club-shaped appearance. The distal limb bones, including the ulna and fibula, are poorly ossified.

Both disorders have a 25% recurrence risk and are potentially detectable in utero by pathogenic variant analysis if the mutant alleles are identified in the parents. Prenatal diagnosis is possible with fetal imaging and/or pathogenic variant testing, which is commercially available.

Diastrophic Dysplasia

Diastrophic dysplasia is a well-characterized disorder recognized at birth by the presence of very short extremities, normal head size, clubfoot, and short hands, with proximal displacement of the thumb producing a hitchhiker appearance (Fig. 738.1). The hands are usually deviated in an ulnar direction. Bony fusion of the metacarpophalangeal joints (symphalangism) is common, as is restricted movement of many joints, including the hips, knees, and elbows. The external ears often become inflamed soon after birth. The inflammation resolves



Fig. 738.2 Radiograph of hands in diastrophic dysplasia. The metacarpals and phalanges are irregular and short. The first metacarpal is ovoid.

spontaneously but leaves the ears fibrotic and contracted (cauliflower ear deformity). Many newborns have a cleft palate.

Radiographs reveal short and broad tubular bones with flared metaphyses and flat, irregular epiphyses (Fig. 738.2). The capital femoral epiphyses are hypoplastic, and the femoral heads are broad. The ulnas and fibulas are disproportionately short. Carpal centers may be developmentally advanced with the first metacarpal typically ovoid, and the metatarsals twisted medially. There may be vertebral abnormalities, including clefts of cervical vertebral lamina and narrowing of the interpedicular distances in the lumbar spine.

Complications are primarily orthopedic and tend to be severe and progressive, leading to joint contractures, spine deformity and early onset OA. The clubfoot deformity in the newborn resists usual treatments, and multiple corrective surgeries are common. Scoliosis typically develops during early childhood. It often requires multiple surgical procedures to control, and it sometimes compromises respiratory function in older children. Despite the orthopedic problems, patients typically have normal intelligence, have normal life span, and reach adult heights in the 105-130 cm range, depending on the severity of scoliosis. Growth curves are available for diastrophic dysplasia. Respiratory insufficiency may present in neonates because of the small rib cage and tracheal instability and collapsibility. In these cases, supportive measures such as mechanical ventilation may be required. Cervical kyphosis is seen in most newborns, which improves spontaneously in childhood. However, some may experience severe cervical kyphosis leading to spinal cord compression.

Some patients are mildly affected and exhibit slight short stature and joint contractures, no clubfoot or cleft palate, and correspondingly mild radiographic changes. The mild phenotype tends to recur within families. The recurrence risk of this autosomal recessive condition is 25%. Ultrasonographic examination can be employed for prenatal diagnosis, but if *TDST* pathogenic variants can be identified in the patients or parents, molecular genetic diagnosis is possible.

AUTOSOMAL RECESSIVE MULTIPLE EPIPHYSEAL DYSPLASIA

Although previously regarded as a multiple epiphyseal dysplasia, according to the new nosology, rMED is now classified among other sulfation disorders. rMED typically presents during adolescence with the gradual onset of hip and knee pain that might resemble rheumatoid arthritis. Later on, patients present with hand, feet, and knee deformities and scoliosis. Fifty percent of individuals present during infancy with club feet and external ear abnormalities. Stature is normal during childhood, but final height might be slightly decreased compared with unaffected siblings and ranges from 150-180 cm. Radiographic findings include flat epiphysis, mild brachydactyly, and double-layered patella. Diagnosis is clinical, based on presentation and radiologic findings, but molecular confirmation is available with a detection rate over 90%. Management includes physical therapy, pain control, and orthopedic interventions.

Chapter 739

Disorders Involving Transcription Factors

Julie E. Hoover-Fong and Daniah Albokhari

Transcription factors are proteins that control the transcription of DNA into RNA to make proteins essential for cellular function. Pathogenic variants in the genes that make transcription factors can result in disease by “turning on” or “turning off” downstream genes to result in disease. Of the estimated 1,500 known transcription factors in humans, four are associated with well-delineated bone dysplasias. Campomelic dysplasia (CD), cleidocranial dysplasia (CCD), and SHOX gene-related conditions are considered dysplasias, whereas nail-patella syndrome (NPS) is classified as a dysostosis (meaning a skeletal disorder limited to individual bones or group of bone rather than the entire skeleton, as in a skeletal dysplasia) (see also Table 735.1).

Pathogenic variants in genes that encode transcription factors that cause disease are SOX9, RUNX2 (CBFA1), SHOX, and LMX1B, respectively. SOX9 is a member of the SOX family of transcription factors related to the SRY (sex-determining region of the Y chromosome) gene; RUNX2 (CBFA1) belongs to the runt family of transcription factor genes; SHOX is part of the homeobox gene family; and LMX1B is part of the LIM homeodomain gene family. Each results in a disorder caused by haploinsufficiency of the respective gene products. CD, CCD, and NPS are all autosomal dominant conditions, whereas SHOX-related conditions are inherited in a pseudodautosomal fashion.

CAMPOMELIC DYSPLASIA

Campomelic dysplasia is apparent in newborn infants and characterized by short, bowed long bones (especially in the lower legs), respiratory distress, cervical spine anomalies, Pierre-Robin sequence, and variable involvement of the central nervous system, heart, and kidneys. In some cases, femoral bowing is minimal (i.e., acampomelic campomelic dysplasia). Additionally, 75% of XY individuals have some degree of gonadal dysgenesis that ranges from normal female phenotype through ambiguous genitalia and lack of determination of testicular tissue with undervirilization. 46,XX individuals have an expected female phenotype with normal ovarian differentiation. *Therefore karyotype analysis is indicated in every female with campomelia.* These features are because of the role of SOX9 in the differentiation of testicular tissue downstream of SRY. Compared with SOX9 haploinsufficiency, duplications cause gonadal tissue to differentiate into testicular tissue in 46,XX individuals, highlighting the dosage sensitivity of SOX9 in gonadal differentiation. Radiographs confirm long bone bowing and often show hypoplasia of the scapulae and pelvic bones (Fig. 739.1). Affected infants often die of respiratory distress in the neonatal period because of tracheomalacia, small thoracic volume, and early scoliosis. Complications in children and adolescents who survive include cervical instability, short stature with progressive kyphoscoliosis, recurrent apnea and respiratory infections, hearing loss, and learning difficulties. Because of a deficiency of gonadal differentiation, 46,XY individuals with female genitalia often present with absent thelarche and primary amenorrhea. Pathogenic variant testing is commercially available and has a >95% detection rate. Nearly all individuals with CD represent a de novo pathogenic variant in SOX9.

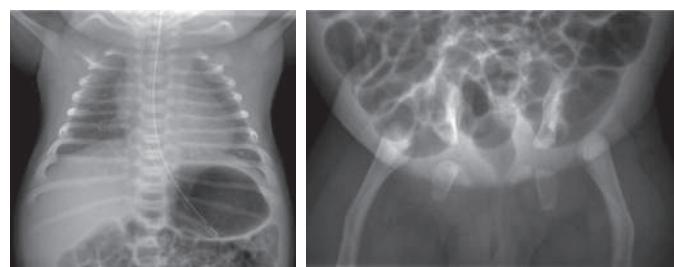


Fig. 739.1 Campomelic dysplasia. Bell-shaped thorax, hypoplastic scapula, bowed femurs, widely spaced ischial bones. (From Campeau P, Schlesinger AE. Skeletal dysplasias [Fig. 12]. [Updated 2017 Jan 30]. In: De Groot LJ, Chrousos G, Dungan K, et al., eds. Endotext [internet]. South Dartmouth, MA, 2000, MDText.com, Inc. Fig 12. Available at <https://www.ncbi.nlm.nih.gov/books/NBK279130/>.)

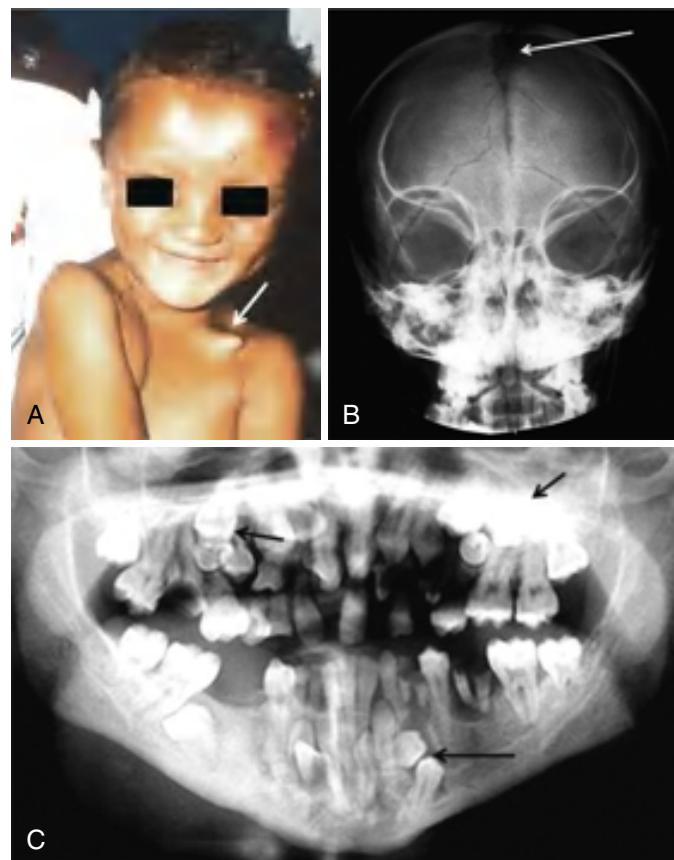


Fig. 739.2 Features of cleidocranial dysplasia displayed. A, The forehead is bulky with a central depression, the eyes are widely spaced, and the jaw is pointed. The clavicle is misshapen (arrow). B, Note patency of the anterior fontanelle. C, Hyperdontia pantomogram of an affected male showing supernumerary teeth. (From Roberts T, Stephen L, Beighton P. Cleidocranial dysplasia: a review of the dental, historical, and practical implications with an overview of the South African experience. *Oral Surg Oral Med Oral Pathol Oral Radiol.* 2013;115[1]:46–55. Figs. 1, 4, and 6.)

CLEIDOCRANIAL DYSPLASIA

Cleidocranial dysplasia can be recognized in infants because of sloping shoulders, wide fontanelles, and prominent forehead. Birth length is normal, but mild short stature and dental abnormalities are evident during childhood (Fig. 739.2). The shoulders of patients



Fig. 739.3 Nail-patella syndrome. A, Adolescent showing nail hypoplasia, especially of thumbs, and displacement of small patellae. B, Two affected children showing nail dysplasia. C, Incomplete extension of the elbows. (From Jones KL, Jones MC, Del Campo M, eds. *Smith's Recognizable Patterns of Human Malformation*, 7th ed. Philadelphia: Saunders, 2013. Fig. 1, p. 574.)

with CD can collapse to meet in the midline because of hypoplasia or absence of the clavicles. Radiographs will reveal the abnormal clavicles, delayed ossification of cranial bones with multiple ossification centers (Wormian bones), and delayed ossification of pelvic bones. The anterior fontanelle is wide and may remain open into adulthood. The course is relatively uncomplicated except for dislocations and variable diffuse joint pain (especially of the shoulders), dental anomalies (e.g., supernumerary and/or retained primary teeth) that require dental treatment, and risk of hearing loss because of infections. Affected individuals are shorter than unaffected siblings and have an increased risk of genu valgum, pes planus, and scoliosis. Diagnosis is based on clinical and radiographic presentation, but molecular confirmation is available with a detection rate of >70%. The proportion of cases caused by de novo pathogenic variants is high. Management includes prevention of ear infections, speech therapy, dental, and orthopedic interventions as indicated.

SHOX GENE-RELATED CONDITIONS

The *SHOX* gene is located on the pseudoautosomal region of the X and Y chromosomes (i.e., Xp22.33/Yp11.32). Because of crossover during meiotic replication, a *SHOX* variant can segregate on both sex chromosomes, thereby allowing inheritance to occur from male to male, male to female, female to female, and female to male (i.e., sex chromosome gene location while appearing to have autosomal inheritance; pseudoautosomal). Haploinsufficiency of the *SHOX* gene (i.e., loss of one copy of the gene) through deletion, single nucleotide variant, or abnormal regulation of adjacent genes causes Leri-Weill dyschondrosteosis (LWD) and idiopathic short stature (ISS) and contributes to Turner syndrome features when included in the absent X-chromosome material. Features of LWD include short stature, mesomelia, and Madelung deformity of the wrists. ISS does not have other phenotypic features of an abnormal *SHOX* gene other than short stature. This distinguishes ISS from Turner syndrome in which the entire X chromosome is typically missing in affected females, causing short stature, pubertal delay/absence, cardiac anomalies, nuchal folds, and other anomalies. Growth hormone injections can provide effective treatment for short stature associated with a *SHOX* gene abnormality.

NAIL-PATELLA SYNDROME

Dysplasia of the nails, absence or hypoplasia of the patella, abnormalities of the elbow, and spurs or "horns" extending from the iliac bones characterize NPS, also called *osteo-onychodysostosis*. Penetrance is high, but clinical presentation is extremely variable with a wide spectrum of severity. Some patients present in early childhood, whereas others are asymptomatic as adults. Nail abnormalities are almost universal with a wide variety of manifestations,

including absence, hypoplasia, clefts, ridged, thin, or hypertrophic nails, all of which may worsen in severity moving in the ulnar to radial direction. Elbow abnormalities include limitation of movement, cubitus valgus, and pterygium. The patella can be hypoplastic or absent (Fig. 739.3). Iliac horns project posterior-laterally from the center of the iliac bone. A total of 30% of patients have nephritis that resembles chronic glomerulonephritis that presents with proteinuria with or without hematuria; 5% of cases progress to end-stage renal disease. There is an increased risk of glaucoma for NPS patients. NPS is often inherited with 12% of cases being *de novo*. Diagnosis is based on clinical presentation, and molecular confirmation is available with a 95% detection rate. Management includes treatment of orthopedic complications, surveillance and treatment of renal disease, and ophthalmologic follow-up.

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Chapter 740

Osteopetrosis and Other Disorders Involving Defective Bone Resorption

Julie E. Hoover-Fong and Daniah Albokhari

Bone dysplasias displaying increased bone density are rare. Osteopetrosis, which has many subtypes, pycnodysostosis, and dysosteosclerosis are the principal members of this disease category. The clinical features and complications of these conditions are the result of abnormal osteoclast formation and function, resulting in defective bone resorption (Table 740.1).

Table 740.1 Osteopetrosis and Related Osteoclast Disorders

GROUP / DISORDER	INHERITANCE	GENE OR LOCUS
Osteopetrosis, neonatal or infantile form	AR	TCIRG, CLCN, SNX10
Osteopetrosis, infantile form, with nervous system involvement	AR	OSTM1
Osteopetrosis, infantile form, osteoclast-poor with immunoglobulin deficiency	AR	TNFRSF11A
Osteopetrosis, intermediate form	AR	TCIRG1, TNFSF11, PLEKHM1, CLCN7
Osteopetrosis, late-onset, dominant form	AD	CLCN7
Osteopetrosis with renal tubular acidosis	AR	CA2
Osteopetrosis with ectodermal dysplasia and immune defect (OLEDAID)	XL	IKBKG
Osteopetrosis, moderate form	AR	SLC4A2
Osteopetrosis, moderate form with defective leucocyte adhesion	AR	FERMT3, RASGRP2
Osteosclerotic metaphyseal dysplasia	AR	LRRK1
Pyknodysostosis	AR	CTSK
Dysosteosclerosis	AR	SLC29A3, TNFRSF11A
Dysosteosclerosis with degenerative encephalopathy and brain malformation	AR	CSF1R

Data from Unger S, Ferreira CR, Mortier GR, et al. Nosology of genetic skeletal disorders: 2023 revision. Am J Med Genet 2023;191A:1164-1209 (Table 1, Group 24, pp 1184-1185).

OSTEOPETROSIS

The term *osteopetrosis* derives from the Greek root “osteo,” meaning bone, and “petrosis,” meaning stone. Osteopetrosis is marked by *increased* bone mass caused by abnormal osteoclast formation or function. The dense bone in osteopetrosis invades the marrow space, causing anemia and pancytopenia, and impinges on nerves traversing cranial and other skeletal foramina, causing deafness, blindness, and palsies. Although the skeleton is dense in osteopetrosis, the bone quality is poor and may be prone to fracture because of imbalanced bone turnover.

To date, genes known to cause osteopetrosis include: *CLCN7*, *TCIRG1*, *OSTM1*, *SNX10*, *CA2*, *PLEKHM1*, *TNFRSF11A*, *TNFSF11*, *IKBKG*, *SLC4A2*, *FERMT3*, and *RASGRP2*. Pathogenic variants in *CLCN7*, *TCIRG1*, *OSTM1*, *SNX10*, *CA2*, and *PLEKHM1* prevent normal osteoclast function to resorb bone while *TNFRSF11A*, *TNFSF11* encode proteins (RANK and RANKL, respectively) that are essential to the formation of osteoclasts. Pathogenic variants in *CLCN7* may cause disease in an autosomal dominant or recessive fashion and variants in *IKBKG* are X-linked, whereas all others here cause recessive osteopetrosis. *CLCN7*-related autosomal dominant osteopetrosis occurs in 1 in 20,000 births, while collectively, the recessive form of osteopetrosis occurs in 1 in 250,000 births. Pathogenic variants in *CLCN7* are the most common cause of osteopetrosis overall, causing a wide spectrum of disease severity ranging from late childhood/adolescent-onset autosomal dominant osteopetrosis II (ADOII) to more involved intermediate autosomal osteopetrosis (IAO) to the most severe autosomal recessive osteopetrosis (ARO) with onset at birth. In general, the other recessive forms of osteopetrosis are also severe, usually detected in infancy because of macrocephaly, hepatosplenomegaly, deafness, blindness, and severe anemia.

CLINICAL MANIFESTATIONS

Most of the manifestations of osteopetrosis are because of failure to remodel growing bones. This leads to narrowing of cranial nerve foramina and encroachment on marrow spaces, which results in secondary complications, such as optic and facial nerve dysfunction, and anemia accompanied by compensatory extramedullary hematopoiesis in the liver and spleen (Table 740.2). The unusually dense bones are weak, leading to increased risk of fractures.

In the severe recessive infancy-onset form, patients present with macrocephaly, hepatosplenomegaly, deafness, blindness, and severe anemia. Radiographs reveal diffuse bone sclerosis and *hypocalcemia* may be present. Later radiographs show the characteristic bone-within-bone appearance throughout the skeleton (Figs. 740.1 and 740.2). With time, infants typically fail to thrive and show psychomotor delay and worsening of cranial neuropathies and anemia. Dental problems, osteomyelitis of the mandible, and pathologic fractures are common. The most severely affected patients die during infancy; less severely affected patients rarely survive beyond the second decade but often only after treatment with bone marrow transplant. Those who survive beyond infancy usually have learning disabilities but might have normal intelligence despite hearing and vision loss.

The autosomal dominant form of osteopetrosis (Albers-Schönberg disease, osteopetrosis tarda, or marble bone disease) usually manifests during childhood or adolescence with fractures and mild anemia and, less often, as cranial nerve dysfunction, dental abnormalities, or osteomyelitis of the mandible. Skeletal radiographs reveal a generalized increase in bone density and clubbing of metaphyses. Alternating lucent and dense bands produce a sandwich appearance to vertebral bodies. The radiographic changes are sometimes incidental findings in otherwise asymptomatic adolescents and adults.

Table 740.2 Complications of Osteopetrosis by Subspecialty

SUBSPECIALTY	COMPLICATION
Endocrinology	Osteopetroneurofibrosis Hypocalcemia
Ophthalmology	Papilledema Ptosis Strabismus Paralysis of extraocular muscles Optic nerve atrophy Exophthalmos Nystagmus Retinal degeneration Tearing (from nasolacrimal duct obstruction)
Dentistry	Delay/failure of tooth eruption Malformed crowns/roots Periodontal ligament defects Odontoma Tooth agenesis Enamel hypoplasia Tooth decay/caries Thickened lamina dura Osteomyelitis (most frequently of the mandible)
Orthopedics	Skeletal deformities Scoliosis Spondylolisthesis Fractures (particularly of the long bones) Delayed union/nonunion Degenerative arthritis Spondylosis
Neurology/ neurosurgery	Compressive cranial neuropathies (often optic and facial nerves, but can involve any of cranial nerves I–VIII) Increased intracranial pressure Craniostenosis Arnold–Chiari I malformation Neuromuscular scoliosis Developmental delay/regression, seizures (<i>OSTM1</i> mutation) Calcifications of the basal ganglia, thalamus (<i>CAL1</i> deficiency) Hydrocephalus Cerebrovascular stenosis/occlusion Acquired encephalocele
Otolaryngology	Conductive hearing loss Recurrent otitis media Chronic congestion (poorly pneumatized sinuses) Rhinorrhea Choanal atresia Rhinosinusitis Obstructive sleep apnea
Hematology	Thrombocytopenia with bleeding Anemia Leukopenia with frequent infections Hepatosplenomegaly Transfusion dependence
Nephrology	Renal tubular acidosis, nephrocalcinosis, and nephrolithiasis (<i>CAL1</i> deficiency)

From Wu CC, Econo MJ, DiMeglio LA, et al. Diagnosis and management of osteopetrosis: consensus guidelines from the osteopetrosis working group. *J Clin Endocrinol Metab* 2017;102(9):3111–3123 (Table 2, p. 3116).

TREATMENT

Most of the bone manifestations in severe osteopetrosis caused by intrinsic osteoclast defects can be prevented or reversed by hematopoietic stem cell transplantation (HSCT), if carried out before development of irreversible secondary complications, such as visual impairment. RANKL replacement therapy may be useful in patients

with RANKL deficiency caused by *TNFSF11* bi-allelic pathogenic variants, who do not benefit from HSCT. Interferon-γ is used to delay progression in patients with severe malignant infantile osteopetrosis. Symptomatic care, such as dental care, transfusions for anemia, and antibiotic treatment of infections, is important for patients who survive infancy.



Fig. 740.1 Osteopetrosis. Thick dense bones, alternating bands of sclerosis, and normal density bone in long bones, rugger jersey spine, dense base of skull. (From Campeau P, Schlesinger AE. *Skeletal dysplasias*. [Updated 2017, Jan 30]. In De Groot LJ, Chrousos G, Dungan K, et al, eds. *Endotext* [internet]. South Dartmouth, MA, 2000, MDText.com, Inc. Fig. 14. Available at <https://www.ncbi.nlm.nih.gov/books/NBK279130/>.)



Fig. 740.2 Osteopetrosis. Right-hand radiograph obtained at 2 weeks of age. Note metaphyseal lucent bands in the distal ulna and radius (arrows) and short tubular bones. (From Stark Z, Savarirayan R. Osteopetrosis. *Orphanet J Rare Dis*. 2009;4:5.)

PYCNODYSOSTOSIS AND DYSOSTEOSCLEROSIS

Pycnodynostosis

An autosomal recessive bone dysplasia related to osteopetrosis, pycnodynostosis manifests in early childhood with short limbs, characteristic facies, an open anterior fontanel, a large skull with frontal and occipital bossing, acroosteolysis, and dental abnormalities. The hands and feet are short and broad, and the nails may be dysplastic. The sclerae may be blue. Minimal trauma often leads to fractures. Treatment is symptomatic and focused mainly on the

management of dental problems and fractures. Although some patients have a persistently open anterior fontanelle (i.e., even into adulthood), others with pycnodynostosis have craniosynostosis. The overall prognosis for these patients is generally good, and they typically reach 130–150 cm in height. Skeletal radiographs show a generalized increase in bone density. In contrast to many disorders in this group, the metaphyses are normal. Other changes include wide sutures and Wormian bones in the skull, a small mandible, and osteolysis of the distal phalanges. Homozygous or compound heterozygous missense, nonsense, insertions, deletions, and splicing variants have been described in the gene *CTSK*, which encodes cathepsin K. This is a lysosomal protease that is involved in bone resorption and remodeling. *CTSK* is highly expressed in osteoclasts, and pathogenic variants prevent degradation of bone matrix proteins (e.g., type I and II collagen), which is necessary for normal bone remodeling and resorption. Growth hormone therapy has been used to improve growth.

Dysosteosclerosis

Dysosteosclerosis is another rare bone disease with generalized increased bone density plus widening of tubular bones and vertebral flattening. It is caused by pathogenic variants in three genes: *SLC9A3*, *CSF1R*, and *TNFRSF11A* (which is allelic with osteopetrosis). Affected individuals have short stature and cranial nerve involvement caused by impingement of the foramina by the abnormally dense bone. No disease-specific treatment has been developed.

There are several other conditions marked by hyperostotic and fragile bones but also other anomalies or conditions distinguishing them from osteopetrosis, pycnodynostosis, and dysosteosclerosis (Table 740.3).

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Table 740.3 Other Conditions with Hyperostotic Fragile Bones

GENE	DISORDER	CLINICAL CHARACTERISTICS	FEATURES DISTINGUISHING THIS DISORDER FROM <i>CLCN7</i> -RELATED ARO
CA2	ARO w/renal tubular acidosis (RTA) (OMIM 259730)	Generalized osteosclerosis. Cerebral calcifications are typical and may be associated with ID.	Onset of ARO with RTA is usually later than in infantile malignant form of ARO and disease course is milder.
OSTM1	OSTM1-related ARO (OMIM 259720)	~4% of ARO is caused by pathogenic variants in <i>OSTM1</i> . Extremely severe form of ARO with CNS involvement that is indistinguishable from most severe forms of <i>CLCN7</i> -related ARO.	<i>OSTM1</i> -related ARO is frequently associated with structural brain anomalies.
PLEKHM1	PLEKHM1-related ARO (OMIM 611497)	Very rare, can look like ADOII.	<i>PLEKHM1</i> -related ARO appears to be very mild and can regress with ↑ age. One person with <i>PLEKHM1</i> -related ARO caused by a heterozygous pathogenic variant has been described.
SNX10	SNX10-related ARO (OMIM 615085)	~4% of ARO is caused by pathogenic variants in <i>SNX10</i> ; in particular, "Västerbottenian osteopetrosis" is caused by <i>SNX10</i> pathogenic variants. Loss of vision, anemia, and bone fragility are frequently observed, warranting use of HSCT.	<i>SNX10</i> -related ARO appears to be slightly less severe than <i>CLCN7</i> -related ARO.
TCIRG1	TCIRG1-related ARO (OMIM 259700)	>50% of ARO is caused by pathogenic variants in <i>TCIRG1</i> .	Higher frequency of neurodevelopmental delay and seizures in <i>CLCN7</i> -related ARO than in <i>TCIRG1</i> -related ARO. Noncoding <i>TCIRG1</i> variants can cause milder phenotype that resembles ADOII.
TNFRSF11A	Osteoclast-poor ARO (OMIM 612301)	Characterized by onset within first year of life and typical ARO manifestations. Investigation of bone biopsy is prerequisite for reliable diagnosis.	TNFSF11 pathogenic variants cause a slight T-cell defect, and <i>TNFRSF11A</i> pathogenic variants can lead to hypogammaglobulinemia similar to common variable immune deficiency. It is crucial to rule out <i>TNFSF11</i> - and <i>TNFRSF11A</i> -related ARO, as HSCT is not successful in these persons.
TNFSF11	Osteoclast-poor ARO (OMIM 259710)		

ADOII, Autosomal dominant osteopetrosis type II; ARO, autosomal recessive osteopetrosis; CNS, central nervous system; ID, intellectual disability; HSCT, hematopoietic stem cell transplantation

From Sobacchi C, Villa A, Schulz A, Kornak U. *CLCN7*-Related Osteopetrosis. 2007 Feb 12 [updated 2022 Jan 20]. In: Adam MP, Ardinger HH, Pagon RA, et al., eds. GeneReviews [Internet]. Seattle (WA): University of Washington, Seattle; 1993–2022.

Chapter 741

Other Inherited Disorders of Skeletal Development

Julie E. Hoover-Fong and Daniah Albokhari

Advances in understanding have led to the delineation of the genetic basis of disorders that were previously poorly understood. Some of these conditions are now classified into gene families based on their molecular and clinical findings, as outlined in the most recent nosology and classification of genetic skeletal disorders and previous chapters. Additional important skeletal dysplasias that do not fit into one of the previous categories are discussed in this chapter.

ELLIS-VAN CREVELD SYNDROME

The Ellis-van Creveld syndrome, also known as **chondroectodermal dysplasia**, is a skeletal *and* an ectodermal dysplasia. This skeletal dysplasia presents at birth with short limbs, especially the middle and

distal segments, accompanied by postaxial polydactyly of the hands and sometimes of the feet (Fig. 741.1). Nail dysplasia and dental anomalies (including neonatal, absent, premature loss of teeth, and upper lip defects) constitute the ectodermal dysplasia. Additional common manifestations include atrial septal defects and other congenital heart defects.

Skeletal radiographs reveal short tubular bones with clubbed ends, especially the proximal tibia and ulna (Fig. 741.2). Carpal bones display extra ossification centers and fusion; cone-shaped epiphyses are evident in the hands. A bony spur is often noted above the medial aspect of the acetabulum.

Ellis-van Creveld syndrome is an autosomal recessive condition that occurs with increased frequency in the Amish and Finnish founder populations than in the general population. Pathogenic variants have been identified in one of two genes, *EVC* (*EVC1*) or *EVC2* (*LIMBIN*), which map in a head-to-head configuration to chromosome 4p. Disease-causing variants of *EVC2* are detected in the allelic condition **Weyers acrofacial dysostosis**. *EVC* and *EVC2* proteins are thought to influence hedgehog signaling in cilia by constitutively associating in a ringlike pattern in the ciliary transition zone and transducing extracellular signals to the nucleus via hedgehog signaling. Fgf18 may also play a significant role. This disorder is classified under the **ciliopathies** with major skeletal involvement (see Chapter 101.3).

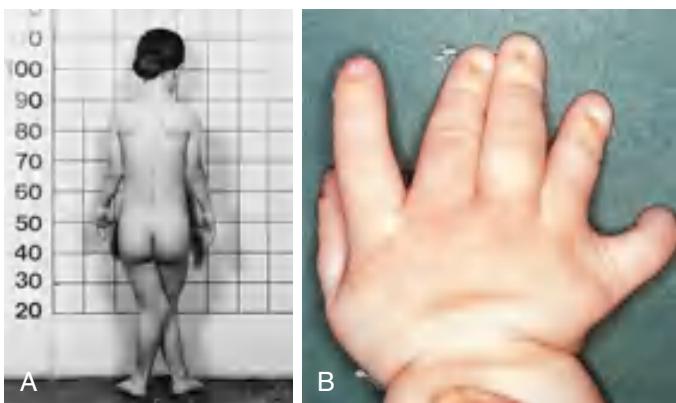


Fig. 741.1 A, Ellis-van Creveld syndrome in a young female. Note short stature, joint contractures at the elbows, and marked genu valgum. B, Multiple digits (polydactyly) in a different patient with Ellis-van Creveld syndrome. (A from Zipes DP, Libby P, Bonow R, Braunwald E, eds. *Braunwald's Heart Disease: a textbook of cardiovascular medicine*, 7th ed. Philadelphia: WB Saunders, 2004. Fig 70.6; B from Beerman LB, Kreutzer J, Allada V. *Cardiology*. In: Zitelli BJ, McIntire SC, Nowalk AJ, eds. *Zitelli and Davis' Atlas of Pediatric Physical Diagnosis*, 6th ed. Philadelphia: Elsevier, 2012. Fig 5.6.)



Fig. 741.2 Radiograph of lower extremities in Ellis-van Creveld syndrome. Tubular bones are short, and proximal fibula is short. Ossification is retarded in lateral tibia epiphyses, causing a knock-knee deformity.

Approximately 30% of patients die of cardiac or respiratory problems during infancy. Life span is otherwise normal; adult heights range from 119–161 cm.

ASPHYXIATING THORACIC DYSTROPHY

See also Chapter 467.3.

Asphyxiating thoracic dystrophy, or **Jeune syndrome**, is an autosomal recessive chondrodysplasia. Newborn infants present with a long, narrow thorax and respiratory insufficiency associated with pulmonary hypoplasia. Neonates often die. Other neonatal manifestations include slightly short limbs and postaxial polydactyly. This condition results from a disturbance of primary cilia, most often from pathogenic variants of the gene encoding cytoplasmic dynein 2 heavy chain 1 (*DYNC2H1*). This disorder is classified under **ciliopathies** with major skeletal involvement (see Chapter 101.3).

Skeletal radiographs show very short ribs with anterior expansion. Tubular limb bones are short with bulbous ends; cone-shaped epiphyses occur in hand bones. The iliac bones are short and square with a spur above the medial aspect of the acetabulum (Fig. 741.3).

If infants survive the neonatal period, respiratory function usually improves as the rib cage grows. Surgery that produces lateral thoracic expansion improves rib growth and enhances chest wall dimensions. Progressive renal dysfunction often develops during childhood. Intestinal malabsorption and hepatic dysfunction have also been reported.

SHORT-RIB POLYDACTYLY SYNDROMES

These conditions, which share the clinical features of constricted thoracic cage, short ribs, polydactyly, very short extremities, lethality during the newborn period and autosomal recessive inheritance. Pathogenic variants that map to cilia-related genes—*DYNC2H1*, *IFT80*, *IFT81*, *WDR34*, *WDR60*, *DYNC2LI1*, *NEK1*, *IFT122*, *WDR19*, *INTU*, *TRAF3IP1*—are found in this group of disorders.

CARTILAGE-HAIR HYPOPLASIA-ANAUXTIC SPECTRUM DISORDERS

Cartilage-hair hypoplasia (CHH), also known as **metaphyseal chondrodysplasia-McKusick type**, is part of a spectrum of disorders with metaphyseal involvement that includes metaphyseal dysplasia without hypotrichosis and anauxetic dysplasia. All disorders are characterized by severe disproportionate short stature, which is usually recognized at birth; the short limbs can lead to prenatal detection. They all show autosomal recessive inheritance and are caused by pathogenic variants in *RMRP*, a gene coding for a large untranslated RNA component of an enzyme complex involved in processing mitochondrial RNA. Loss of this gene product interferes with processing of both messenger RNA and ribosomal RNA and correlates with the extent of bone dysplasia, whereas loss of messenger RNA processing correlates with the degree of hair hypoplasia, immunodeficiency, and hematologic abnormality. Molecular testing confirms the diagnosis, and prenatal diagnosis is available if the pathogenic variant is identified either in the patient or the parents.

CHH is recognized during the second year because of growth deficiency affecting the limbs, accompanied by flaring of the lower rib cage, a prominent sternum, and bowing of the legs. The hands and feet are short, and the fingers are very short with extreme ligamentous laxity. The hair is thin, sparse, and light colored; the nails are hypoplastic; and the skin can be hypopigmented.

Radiographs show short tubular bones with flared, irregularly mineralized, and cupped metaphyses (Fig. 741.4). The knees are more affected than are the hips, and the fibula is disproportionately longer than the tibia. The metacarpals and phalanges are short and broad. Spinal radiographs reveal mild platyspondyly.

Nonskeletal manifestations associated with CHH include immunodeficiency (T-cell abnormalities, neutropenia, leukopenia, and susceptibility to varicella zoster virus infections; children also may have complications from smallpox and polio vaccinations), malabsorption, celiac disease, and Hirschsprung disease. Adults are at risk for malignancy, especially non-Hodgkin lymphoma and skin tumors. Adult height ranges from 107–157 cm.

The highest birth prevalence is in the Amish and Finnish populations because of a founder effect. Carrier frequency in the Amish is 1:19 with 1 per 1,300 births affected compared to a carrier frequency of 1:76 and 1 per 23,000 births affected in Finland. The exact prevalence in the general population is not known, but CHH

is relatively rare. However, two allelic conditions, metaphyseal dysplasia without hypotrichosis and anauxetic dysplasia, expand the phenotypic spectrum. Children with a growth disorder and abnormal hair should be evaluated for *RMRP* pathogenic variants.

TRPV4-SPECTRUM DISORDERS

Pathogenic variants in *TRPV4* cause a spectrum of conditions including metatropic dysplasia, spondylometaphyseal dysplasia (SMD), Kozlowski type, brachyolmia, and familial digital arthropathy with brachydactyly. Metatropic dysplasia and SMD, Kozlowski type are expanded on next. **Brachyolmia** is dominated by progressive scoliosis and platyspondyly on x-rays and familial digital arthropathy with brachydactyly, which is characterized by deforming painful osteoarthritis of the interphalangeal, metacarpophalangeal, and metatarsophalangeal joints starting after the first decade of life. The rest of the skeleton is unaffected in this condition. It should also be noted that pathogenic variants in *TRPV4* are also responsible for a large group of neuromuscular disorders including **Charcot-Marie-Tooth disease type 2C**, scapuloperoneal spinal muscular atrophy, and congenital distal spinal muscular atrophy. Though there is considerable overlap of the phenotypes of the conditions within the skeletal group and the neuromuscular group, there are only rare instances currently recognized of individual patients with both features.

METATROPIC DYSPLASIA

Metatropic dysplasia is an autosomal dominant disorder resulting from heterozygous pathogenic variants of transient receptor potential vanilloid family 4 (*TRPV4*), which encodes a calcium-permeable cation channel. Newborn infants present with a long narrow trunk and short extremities. A tail-like appendage sometimes extends from the base of the spine. Odontoid hypoplasia is common and may be associated with cervical instability. Kyphoscoliosis appears in late infancy and progresses through childhood, often becoming severe enough to compromise cardiopulmonary function. The joints are large and become progressively restricted in mobility, except in the hands. Contractures often develop in the hips and knees during childhood. Although severely affected infants can die at a young age from respiratory failure, patients usually survive, although they can become disabled as adults from the

progressive musculoskeletal deformities. Adult heights range from 110–120 cm.

Skeletal radiographs show characteristic changes dominated by severe platyspondyly and short tubular bones with expanded and deformed metaphyses that exhibit a dumbbell appearance (Fig. 741.5). The pelvic bones are hypoplastic and exhibit a halberd appearance because of a small sacrosciatic notch and a notch above the lateral margin of the acetabulum.



Fig. 741.4 Radiograph of lower extremities in cartilage-hair hypoplasia. The tubular bones are short, and the metaphyses are flared and irregular. The fibula is disproportionately long compared with the tibia. The femoral necks are short.



Fig. 741.3 Asphyxiating thoracic dystrophy. Short ribs, long and narrow chest, small pelvis, trident acetabula, no platyspondyly (helps differentiate from thanatophoric dysplasia), cystic renal disease. (From Campeau P, Schlesinger AE. Skeletal dysplasias. [Updated 2017 Jan 30]. In: De Groot LJ, Chrousos G, Dungan K, et al., eds. Endotext [internet]. South Dartmouth, MA, 2000, MDText.com, Inc., Fig 6. Available at: <https://www.ncbi.nlm.nih.gov/books/NBK279130/>)

SPONDYLOMETAPHYSEAL DYSPLASIA, KOZLOWSKI TYPE

Kozlowski type of spondylometaphyseal dysplasia is an autosomal dominant allelic disorder to metatropic dysplasia caused by *TRPV4* variants.

Kozlowski type of spondylometaphyseal dysplasia manifests in early childhood with mild short stature involving mostly the trunk and a waddling gait. The hands and feet may be short and stubby. Radiographs show flattening of vertebral bodies. The metaphyses of tubular bones are widened and irregularly mineralized, especially at the proximal femur. The pelvic bones manifest mild hypoplasia. Scoliosis can develop during adolescence. The disorder is otherwise uncomplicated, and manifestations are limited to the skeleton. Adults reach heights of 130–150 cm.

DISORDERS INVOLVING FILAMINS

Pathogenic variants of genes encoding filamin A and filamin B proteins have been detected in diverse disorders of skeletal development: filamin A pathogenic variants in otopalatodigital syndromes type 1 and 2, frontometaphyseal dysplasia, Melnick-Needles syndrome and terminal osseous dysplasia with pigmentary defects and filamin B pathogenic variants in Larsen syndrome and perinatal lethal atelosteogenesis types

1 and 3, spondyo-carpal-tarsal dysplasia and Boomerang dysplasia. Filamins functionally connect extracellular to intracellular structural proteins, thereby linking cells to their local microenvironment, which is essential for skeletal development and growth.

JUVENILE OSTEOCHONDROSES

The juvenile osteochondroses are a heterogeneous group of disorders in which regional disturbances in bone growth cause non-inflammatory arthropathies. Table 741.1 summarizes the juvenile osteochondroses. Some have localized pain and tenderness (Freiberg disease, Osgood-Schlatter disease [see Chapter 718.4], osteochondritis dissecans [see Chapter 718.3]), whereas others present with painless limitation of joint movement (Legg-Calvé-Perthes disease [see Chapter 719.3], Scheuermann disease [see Chapter 720.4]). Bone growth may be disrupted, leading to deformities. The diagnosis is usually confirmed radiographically, and treatment is symptomatic. The pathogenesis of these disorders is believed to involve ischemic necrosis of primary and secondary ossification centers. Although familial forms have been reported, these disorders usually occur sporadically.

CAFFEY DISEASE (INFANTILE CORTICAL HYPEROSTOSIS)

This is a rare disorder of unknown etiology characterized by cortical hyperostosis with inflammation of the contiguous fascia and muscle. It is often sporadic, but both autosomal dominant and autosomal recessive forms have been reported. Pathogenic variants in *FAM111A* and *TBCE* have been identified in the autosomal dominant and recessive forms, respectively. **Sanjad-Sakati syndrome** (hypoparathyroidism, intellectual disability, dysmorphism) is also caused by pathogenic variants in *TBCE*. Caffey dysplasia is classified in the slender bone dysplasia group.

Prenatal and more often postnatal onsets have been described. Prenatal onset may be mild (autosomal dominant) or severe (autosomal recessive). Severe prenatal disease is characterized by typical bone lesions, polyhydramnios, hydrops fetalis, severe respiratory distress, prematurity, and high mortality. Onset in infancy (younger than 6 months; average: 10 weeks) is most common; manifestations include the sudden onset of irritability, swelling of contiguous soft tissue that precedes the cortical thickening of the underlying bones, fever, and anorexia. The swelling is painful with a woodlike induration but with minimal warmth or redness; suppuration is absent. There are unpredictable remissions and relapses; an episode can last 2 weeks to 3 months. The most common bones involved include the mandible (75%) (Fig. 741.6), the clavicle, and the ulna. If swelling is not prominent or visible, the diagnosis might not be evident.

Laboratory features include elevated erythrocyte sedimentation rate and serum alkaline phosphatase as well as, in some patients, increased serum prostaglandin E levels. There may be

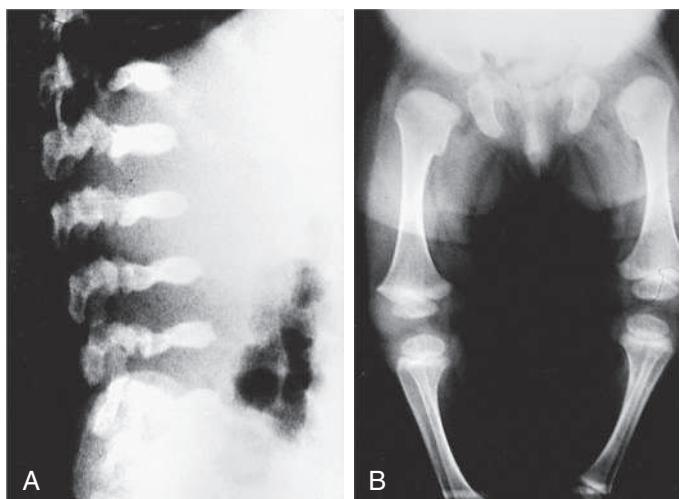


Fig. 741.5 A, Radiograph of the lateral thoracolumbar spine in metatropic dysplasia showing severe platyspondyly. B, Radiograph of lower extremities in metatropic dysplasia showing short tubular bones with widened metaphyses. The femurs have a dumbbell appearance.

Table 741.1 Juvenile Osteochondroses

EPONYM	AFFECTED REGION	AGE AT PRESENTATION
Legg-Calvé-Perthes disease	Capital femoral epiphysis	3-12 yr
Osgood-Schlatter disease	Tibial tubercle	10-16 yr
Sever disease	Os calcaneus	6-10 yr
Freiberg disease	Head of second metatarsal	10-14 yr
Scheuermann disease	Vertebral bodies	Adolescence
Blount disease	Medial aspect of proximal tibial epiphysis	Infancy or adolescence
Osteochondritis dissecans	Subchondral regions of knee, hip, elbow, and ankle	Adolescence



Fig. 741.6 Facies in infantile cortical hyperostosis. In almost all cases, the changes have appeared before the fifth month of life. Unilateral swelling of the left cheek and left side of the jaw in an infant 12 weeks of age. (From Slovis T, ed. Caffey's Pediatric Diagnostic Imaging, 11th ed. Philadelphia: Mosby, 2008.)

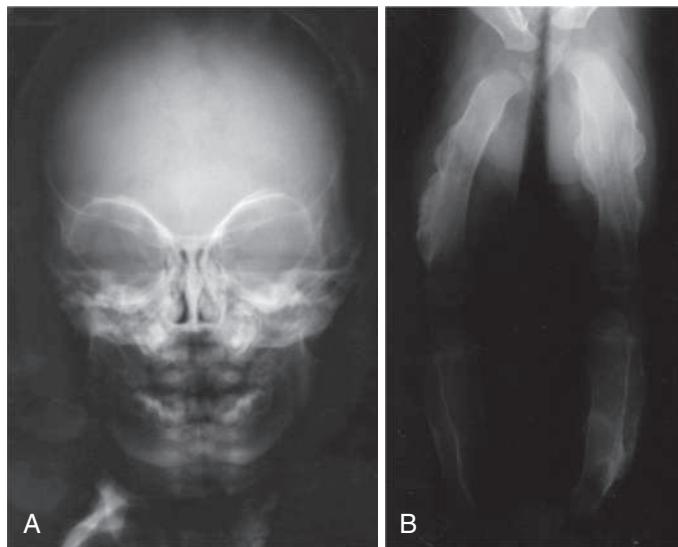


Fig. 741.7 A, Radiograph of a 5-mo-old infant showing hyperostosis of the mandible. B, Radiograph of a 5-mo-old infant showing hyperostosis of both legs. (From Kamoun-Goldrat A, le Merrer M. Infantile cortical hyperostosis [Caffey disease]: a review. *J Oral Maxillofac Surg*. 2008;66:2145–2150. Figs. 1 and 2.)

thrombocytosis and anemia. The radiographic features include soft tissue swelling and calcification and cortical hyperostosis (Fig. 741.7). All bones may be affected except the phalanges or vertebral bodies. The differential diagnosis includes other causes of hyperostosis such as chronic vitamin A intoxication, prolonged prostaglandin E infusion in children with ductal dependent congenital heart disease, primary bone tumors, and scurvy.

Complications are unusual but include pseudoparalysis with limb or scapula involvement, pleural effusions (rib), torticollis (clavicle), mandibular asymmetry, bone fusion (ribs or ulna and radius), and bone angulation deformities (common with severe prenatal onset). Treatment includes indomethacin and prednisone (if there is a poor response to indomethacin).

FIBRODYSPLASIA OSSIFICANS PROGRESSIVA

Fibrodysplasia ossificans progressiva (FOP) is a rare and severely disabling disorder characterized by progressive extraskeletal heterotopic bone formation in soft connective tissues including muscles, tendons, ligaments, fascia, and aponeuroses. With the exception of deformity of the large toes, infants are normal at birth. Episodes of painful soft tissue swelling with inflammation usually begin in early childhood initially involving the upper back and neck, and later the entire trunk and extremities. Repeated episodes (flare-ups) slowly transform the soft tissues into bands or plates of bone that span joints and progressively limit movement and mobility. Episodes are often triggered by injury, intramuscular injections, and viral infection. Most patients are wheelchair bound by their late teens. The average life span is approximately 40 years, with death usually resulting from complications of thoracic insufficiency.

FOP results from heterozygous activating pathogenic variants of the gene (*ACVR1*) encoding the bone morphogenetic protein (BMP) type I receptor, activin A receptor type I (*ALK2*). Patients with classic FOP have the same missense *ACVR1* pathogenic variant, which enhances BMP signaling, which, in turn, induces inflammation and aberrant endochondral ossification through mechanisms that are poorly understood. Environmental factors, such as injury, play an important role in triggering these events. *ACVR1* pathogenic variants usually occur sporadically, but autosomal dominant transmission has rarely been observed. FOP is classified in the disorganized development of skeletal components group.

There is currently no definitive treatment for FOP. Supportive care includes avoidance of injury-prone physical activities, intramuscular injections including immunizations, and overstretching of the jaw during dental procedures. Corticosteroids and other anti-inflammatory agents reduce inflammation and pain during flare-ups but are unable to prevent heterotopic bone formation. Studies in FOP animal models suggest that BMP type I kinase inhibitors and retinoic acid receptor γ agonists, which block chondrogenesis—the initial step in endochondral ossification—may be useful therapies in the future. An animal FOP study has indicated that mutant *ALK2* responds to activin A, induces canonical BMP signaling, and leads to heterotopic bone formation, providing an additional possible therapeutic target. The retinoic acid receptor γ agonist palovarotene was approved by the US Food and Drug Administration in 2023 for treatment of FOP for females ages 8 years and older and for males ages 10 years and older.

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Chapter 742

Osteogenesis Imperfecta

Joan C. Marini

Osteoporosis is fragility of the skeletal system and a susceptibility to fractures of the long bones or vertebral compressions from mild or inconsequential trauma (see Chapter 749). **Osteogenesis imperfecta (OI)** (brittle bone disease), the most common genetic cause of osteoporosis, is a generalized disorder of connective tissue. The spectrum of OI is extremely broad, ranging from forms that are lethal in the perinatal period to a mild form in which the diagnosis may be equivocal in an adult (Table 742.1).

Etiology

Structural or quantitative defects in type I collagen cause the full clinical spectrum of OI (types I-IV). Defects in processing either the N- or C-terminal propeptides of type I collagen cause distinctive bone fragility syndromes. Type I collagen is the primary component of the extracellular matrix of bone and skin. Between 15% and 20% of patients clinically indistinguishable from OI do not have a molecular defect in type I collagen. These cases are typically caused by defects in genes whose protein products interact with type I collagen. One group of patients has overmodified collagen, with similar biochemical findings to those with collagen structural defects and severe or lethal OI bone dysplasia. These cases are caused by recessive null pathogenic variants in any of the three components of the collagen prolyl 3-hydroxylation complex, prolyl 3-hydroxylase 1 (encoded by *LEPRE1*) or its associated protein, CRTAP, or cyclophilin B (CyPB, encoded by *PPIB*). A second set of cases without collagen defects have biochemically normal collagen. Defects in *IFITM5* and *SERPINF1* account for defects in mineralization in types V and VI OI, while pathogenic variants in *SERPINH1*, encoding the collagen chaperone HSP47, and *FKBP10*, encoding the peptidyl-prolyl *cis-trans* isomerase FKBP65, cause types X and XI OI, respectively. Rare pathogenic variants in *BMP1*, the enzyme that processes the C-propeptide of type I collagen, also cause a recessive form of OI (type XIII). The newest set of genes added to the recessive OI causative panel (*SP7*, type XII OI; *TMEM38B*, type XIV OI; *WNT1*, type XV OI; *CREB3L1*, type XVI OI, *SPARC*, type XVII OI, and *MBTPS2*, type XVIII OI) are not only involved in osteoblast differentiation but also affect collagen synthesis and cross linking. There are currently very few individuals with OI whose genetic defect is not in a known causative gene.

Epidemiology

The autosomal dominant forms of OI occur equally in all racial and ethnic groups, whereas recessive forms occur predominantly in ethnic groups with consanguineous marriages or as a founder effect in an isolated population. The West African founder pathogenic variant for type VIII OI has a carrier frequency of 1 in 200–300 among Black individuals. The collective incidence of all types of OI detectable in infancy is approximately 1 in 20,000. There is a similar incidence of the mild form OI type I.

Pathology

The pathogenic structural collagen variants in OI cause the bones to be globally abnormal. The bone matrix contains abnormal type I collagen fibrils and relatively increased levels of types III and V collagen. Several noncollagenous proteins of bone matrix are also reduced. Bone cells also contribute to OI pathology, with abnormal osteoblast differentiation and increased numbers of active bone resorbing osteoclasts. The hydroxyapatite crystals deposited on this matrix are poorly aligned with the long axis of fibrils, and there is paradoxical hypermineralization of bone.

Pathogenesis

Type I collagen is a heterotrimer composed of two $\alpha_1(I)$ chains and one $\alpha_2(I)$ chain. The chains are synthesized as procollagen molecules with short globular propeptide extensions on both ends of the central helical domain. The helical domain is composed of uninterrupted repeats of the sequence Gly-X-Y, where Gly is glycine, X is often proline, and Y is often hydroxyproline. The presence of glycine at every third residue is crucial to helix formation because its small side chain can be accommodated in the interior of the helix. The chains are assembled into trimers at their carboxyl ends, and helix formation then proceeds linearly in a carboxyl to amino direction. Concomitant with helix assembly and formation, helical proline and lysine residues are hydroxylated by prolyl 4-hydroxylase and lysyl hydroxylase 1, and some of the hydroxylysine residues are subsequently glycosylated. After secretion, the propeptides are cleaved in the pericellular space by specific N- and C-terminal propeptidases.

Collagen structural defects are predominantly of two types: 80% are pathogenic missense variants causing substitutions of helical glycine residues or crucial residues in the C-propeptide by other amino acids, and 20% are single exon splicing defects. The clinically mild OI type I has a quantitative defect, with null pathogenic variants in one $\alpha_1(I)$ allele leading to a reduced amount of normal collagen. Deficiency of type I procollagen caused by a C-propeptide removal causes a paradoxical high bone mass form of OI with mild or severe skeletal fragility depending on whether the defect is in the cleavage site or the cleaving peptidase. Impaired removal of the N-propeptide causes an overlap syndrome of Ehlers-Danlos and OI (OI/EDS) with variable skeletal fragility.

Glycine substitutions in the two α chains have distinct genotype-phenotype relationships, but there is also striking phenotype variability caused by independent pathogenic variants at the same site. In general, glycine substitutions in the α_1 chain are more lethal than those in the $\alpha_2(I)$ chain. Two lethal regions in $\alpha_1(I)$ align with major ligand binding regions of the collagen helix.

Classical OI (Sillence types I-IV) is an autosomal dominant disorder, as is type V OI. Some familial recurrences of OI are caused by parental mosaicism for dominant collagen pathogenic variants. Recessive OI accounts for 10–15% of newly diagnosed OI in North America. Three recessive types are caused by null pathogenic variants in the genes coding for the components of the collagen prolyl 3-hydroxylation complex in the endoplasmic reticulum (*LEPRE1*, *CRTAP*, or *PPIB*). Murine models indicate that it is the absence of the complex components, rather than the absence of the Pro986 modification, that is critical for development of OI. Other recessive types are caused by null pathogenic variants in genes whose products are involved in collagen folding (*SERPINH1*, *FKBP10*), bone mineralization (*SERPINF1*), or defects in osteoblast differentiation and function (*SP7*, *TMEM38B*, *WNT1*, *CREB3L1*, *SPARC*, *MBTPS2*).

Clinical Manifestations

Classical OI was described with the triad of fragile bones, blue sclerae, and early deafness, although most cases do not have all three features. The Sillence classification divides OI into four types based on clinical and radiographic criteria. Types V and VI were later proposed based on histologic distinctions. Subsequent types VII–XVIII were based on identification of the molecular defect, followed by clinical description.

Osteogenesis Imperfecta Type I (Mild)

OI type I is sufficiently mild that it is often found in large pedigrees. Many type I families have blue sclerae, recurrent fractures in childhood, and presenile (i.e., beginning in early adulthood) hearing loss (30–60%). Both types I and IV are divided into A and B subtypes, depending on the absence (A) or presence (B) of **dentinogenesis imperfecta**, a type of dentin dysplasia resulting in discolored (often blue-gray or amber), translucent teeth that wear down rapidly or break. Other possible connective tissue abnormalities include hyperextensible joints, easy bruising, thin skin, joint laxity, scoliosis, wormian bones, hernia, and mild short stature compared with family members. Fractures result from mild to moderate trauma but decrease after puberty.

DISORDER	INHERITANCE	GENE	PREVIOUS NAMES / NOTATION
Osteogenesis imperfecta, non-deforming (Sillence type 1)	AD	COL1A1, COL1A2	OMIM as OI type I
Osteogenesis imperfecta, severe perinatal form (Sillence type 2)	AD	COL1A1, COL1A2	OMIM as OI type II
	AR	CRTAP	OMIM as OI type VII
	AR	P3H1	OMIM as OI type VIII
	AR	PPIB	OMIM as OI type IX
Osteogenesis imperfecta, progressively deforming (Sillence type 3)	AD	COL1A1, COL1A2, IFITM5	OMIM as OI type III
	AD	SERPINF1	In OMIM as OI type VI
	AR	CRTAP, P3H1	OMIM as OI type VII
	AR	PPIB	OMIM as OI type IX
	AR	SERPINH1	OMIM OI as type X
	AR	FKBP10	OMIM as OI type XI
	AR	TMEM38B	OMIM as OI type XIV
	AR	BMP1	OMIM as OI type XIII
	AR	WNT1	OMIM as OI type XV Variants may result in AD osteoporosis.
	AR	CREB3L1	OMIM as OI type XVI Ehlers-Danlos-like
	AR	SPARC	OMIM as OI type XVII
	AR	TENT5A	OMIM as OI type XVIII
	XLR	MBTPS2	OMIM as OI type XIX
	AR	MESD	OMIM as OI type XX
Osteogenesis imperfecta, moderate form (Sillence type 4)	AD	KDELR2	OMIM as OI type XXL
	AR	CCD134	OMIM as OI type XXII
	AD	COL1A1, COL1A2, IFITM5	OMIM as OI type IV
	AR	WNT1	OMIM as OI type XV
	AR	CRTAP	OMIM as OI type VII
	AD	PP1B	OMIM as OI type IX
Osteogenesis imperfecta with calcification of interosseous membranes and/or hypertrophic callus (OI type 5)	AR	FKBP10	OMIM as OI type XI
	AR	SP7	OMIM as OI type XII
	AD	IFITM5	May mimic progressively deforming or moderate OI (Sillence types 3 and 4)
Osteogenesis imperfecta with craniosynostosis (Cole-Carpenter syndrome)	AD	P4HB	Craniosynostosis is not well documented.
	AR	SEC24D	Most patients do not have craniosynostosis but rather large fontanelles.
Osteoporosis – X-linked form	XL	MBTPS2	OMIM as OI type XIX
Osteoporosis – dominant form	AD	WNT1	OMIM as OI type XV

Data from Unger S, Ferreira CR, Mortier GR, et al: Nosology of genetic skeletal disorders: 2023 revision. Am J Med Genet 2023;191A:1164-1209 (Table 1, Group 26, pp. 1187-1190).

Osteogenesis Imperfecta Type II (Perinatal Lethal)

Infants with OI type II may be stillborn or die in the first years of life. Birthweight and length are small for gestational age. There is extreme fragility of the skeleton and other connective tissues. There are multiple intrauterine fractures of long bones, which have a crumpled appearance on radiographs. There are striking micromelia and bowing of

extremities; the legs are held abducted at right angles to the body in the frogleg position. Multiple rib fractures create a beaded appearance, and the small thorax contributes to respiratory insufficiency. The skull is large for body size, with enlarged anterior and posterior fontanelles. Sclerae are dark blue-gray. The cerebral cortex has multiple neuronal migration and other defects (agyria, gliosis, periventricular leukomalacia).



Fig. 742.1 Infant with type III osteogenesis imperfecta displays shortened bowed extremities, thoracic deformity, and relative macrocephaly.

Osteogenesis Imperfecta Type III (Progressive Deforming)

OI type III is the most severe nonlethal form of OI and results in significant physical disability. Birthweight and length are often low normal. Fractures usually occur in utero. There is relative macrocephaly and triangular facies (Fig. 742.1). Postnatally, fractures occur from inconsequential trauma and heal with deformity. Disorganization of the bone matrix results in a “popcorn” appearance at the metaphyses (Fig. 742.2). The rib cage has flaring at the base, and pectus deformity is frequent. Virtually all type III patients have scoliosis and vertebral compression. Growth falls below the curve by the first year; all type III patients have extreme short stature. Scleral hue ranges from white to blue. Dentinogenesis imperfecta, hearing loss, and kyphoscoliosis may be present or develop over time.

Osteogenesis Imperfecta Type IV (Moderately Severe)

Patients with OI type IV can present at birth with in utero fractures or bowing of lower long bones. They can also present with recurrent fractures after ambulation and have normal to moderate short stature. Most children have moderate bowing even with infrequent fractures. Children with OI type IV require orthopedic and rehabilitation intervention, but they are usually able to attain community ambulation skills. Fracture rates decrease after puberty. Radiographically, they are osteoporotic and have metaphyseal flaring and vertebral compressions. Scleral hue may be blue or white.

Defects in the Processing of Type I Procollagen Propeptides

Autosomal dominant pathogenic variants in the C-propeptide cleavage site of procollagen or recessive defects in *BMP1*, the enzyme responsible for its cleavage, cause bone fragility with normal or elevated dual-energy x-ray absorptiometry bone density *z* scores. Individuals with dominant pathogenic variants have normal stature, white sclerae and teeth, and mild to moderate OI. Null pathogenic variants in *BMP1* lead to a more severe skeletal phenotype with short stature, scoliosis, and

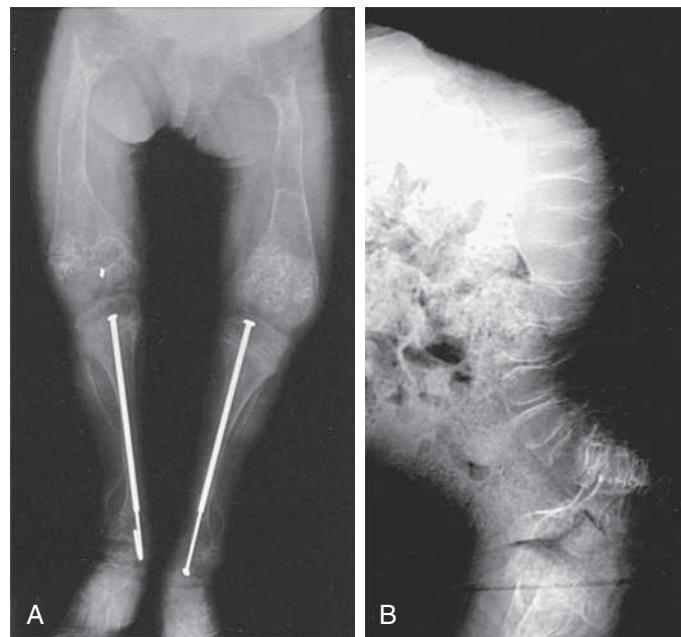


Fig. 742.2 Typical features of type III osteogenesis imperfecta radiographs in a 6-yr-old child. A, Lower long bones are osteoporotic, with metaphyseal flaring, “popcorn” formation at growth plates, and placement of intramedullary rods. B, Vertebral bodies are compressed and osteoporotic.

bone deformity because *BMP1* has other substrates in addition to type I collagen.

Defects in removal of the type I procollagen N-propeptide cause a distinctive combination of Ehlers-Danlos syndrome and OI. Deletion of exon six, containing the cleavage site, causes EDS type VII. Glycine substitutions near the cleavage site impair processing by altering the site configuration, causing hyperextensibility of large and small joints and variable bone fragility.

Osteogenesis Imperfecta Type V (Hyperplastic Callus) and Type VI Hyperosteoidosis (Mineralization Defect)

Types V and VI OI patients clinically have OI similar in skeletal severity to types IV and III, respectively, but they have distinct findings on bone histology. Type V patients also usually have some combination of hyperplastic callus, calcification of the interosseous membrane of the forearm, and/or a radiodense metaphyseal band. They constitute <5% of OI cases. All type V OI patients are heterozygous for the same pathogenic variant in *IFITM5*, which generates a novel start codon for the bone protein BRIL. Ligamentous laxity may be present; blue sclera or dentinogenesis imperfecta are not present. Patients with type VI OI have progressive deforming OI that does not manifest at birth. They have distinctive bone histology with broad osteoid seams and fish-scale lamellation under polarized light, caused by deficiency of pigment epithelium derived factor, encoded by *SERPINF1*. Types V and VI are connected in intracellular osteoblast pathways—*SERPINF1* transcripts are increased in type V OI, while *IFITM5* transcripts are decreased in type VI OI.

Osteogenesis Imperfecta Types VII, VIII, and IX (Autosomal Recessive)

Types VII and VIII patients overlap clinically with types II and III OI but have distinct features including white sclerae, rhizomelia, and small to normal head circumference. Surviving children have severe osteochondrodysplasia with extreme short stature and dual-energy x-ray absorptiometry L1-L2 *z* score in the -6 to -7 range. Type IX OI is very rare; most cases are lethal, but some have moderate skeletal severity without rhizomelia, and white sclerae.

Osteogenesis Imperfecta Types X and XI (Autosomal Recessive)

There have been several reports of severe to lethal type X OI caused by defects affecting the serine-type endopeptidase inhibitor domain of HSP47. This domain is responsible for the HSP47 chaperone function that helps to maintain the folded state of procollagen heterotrimers. HSP47 and FKBP65, the protein responsible for type XI OI, cooperate in collagen synthesis. Type XI OI is a more prevalent recessive form with a moderate to severe skeletal phenotype, including white sclerae and normal teeth. Congenital contractures of large joints may occur with the same pathogenic variants that cause only skeletal fragility, even in sibships. At the opposite end of the spectrum, a deletion of a single tyrosine residue causes Kuskokwim syndrome, a congenital contracture disorder with very mild vertebral findings and osteopenia. Defects in *FKBP10* decrease collagen cross-linking in matrix because FKBP65 is the foldase for lysyl hydroxylase 2, which hydroxylates collagen telopeptide residues important for cross linking.

Defects in Osteoblast Differentiation (Types XIII–XXII OI)

The most recent functional grouping of genes causing recessive OI (types XIII to XXII) affect osteoblast differentiation and are collagen related. *SP7* (type XIII OI) regulates osteoblast differentiation and is critical for bone formation. *TMEM38B* (type XIV OI) defects are clinically indistinguishable from type IV OI. *TMEM38B* encodes the endoplasmic reticulum membrane cation channel TRIC-B, which affects calcium flux from the endoplasmic reticulum to the cytoplasm. Since many enzymes involved in collagen metabolism are calcium dependent, collagen synthesis is globally dysregulated in the absence of TRIC-B, with significant intracellular retention. Collagen posttranslational modification is also impaired, leading to underhydroxylation of the collagen helix. Recessive *WNT1* (type XV OI) defects cause severe progressive deforming OI. Notably, Wnt signaling pathway activation through the Frizzled receptor on the osteoblast surface increases bone mass, and deficiency of Wnt decreases it. *SPARC* (type XVII OI), also known as osteonectin, is a glycoprotein component of extracellular matrix. Defects in residues important for SPARC binding to collagen were reported in two cases of moderate to severe OI.

The genes *MBTPS2* and *CREB3L1*, causing types XVIII and XVI OI, respectively, encode proteins involved in regulated intramembrane proteolysis (RIP). *MBTPS2* encodes the transmembrane Golgi protein site-2 protease (S2P), that acts in succession with S1P to activate regulatory molecules in times of cell stress. OASIS, encoded by *CREB3L1*, is an RIP substrate.

Interestingly, missense substitutions in S2P in OI patients result in underhydroxylation of the collagen lysine residue important for crosslinking of collagen in matrix, thus impairing bone strength. In OASIS-null mice, collagen transcription has been shown to be impaired.

Defects in *TENT5A*, *MESD*, *KDELR2*, and *CCDC134* have been reported in small numbers of individuals with lethal or severe OI skeletal phenotypes. The products of these genes are not known to interact directly with collagen. *TENT5A* encodes FAM46A, a cytoplasmic poly(A) polymerase with an unexpected role in bone mineralization, likely related to its role as a binding partner for SMADs, modulating BMP signaling. *MESD* acts along the Wnt pathway, serving as an endoplasmic reticulum chaperone for the low-density lipoprotein receptors LRP5 and LRP6. Oligodontia and intellectual disability occur in some patients. Bone histology shows enlarged osteocytes and irregular matrix mineralization.

Pathogenic variants in *KDELR2* cause neurodevelopmental and severe skeletal defects. Pathogenic variants in *CCDC134* add to the skeletal effects by impacting the mitogen-activated protein kinase/extracellular signal-regulated kinase (MAPK/ERK) pathway. Expression of type I collagen is reduced, as is osteoblast in vitro mineralization, but histomorphometry is atypical for OI.

LABORATORY FINDINGS

DNA sequencing is the first diagnostic laboratory test, and several Clinical Laboratory Improvement Amendments (CLIA)-certified sequencing labs offer panels to test for dominant and recessive OI. Pathogenic variant identification is useful to determine the type with certainty and to facilitate family screening and prenatal diagnosis. It is also possible to screen for type VI OI by the determination of serum pigment epithelium-derived factor level, which is severely reduced in this type.

If dermal fibroblasts are obtained, they can be useful for determining the level of transcripts of the candidate gene and for collagen biochemical testing, which is positive for overmodification in most cases of types I–IV and IX OI, and in all cases of VII/VIII OI, and for undermodification in type XIV. In OI type I, the reduced amount of type I collagen results in an increase in the ratio of type III to type I collagen on gel electrophoresis.

Severe OI can be detected prenatally by level II ultrasonography as early as 16 weeks of gestation. OI and thanatophoric dysplasia may be confused. Fetal ultrasonography might not detect OI type IV and rarely detects OI type I. For recurrent cases, chorionic villus biopsy can be used for biochemical or molecular studies. Amniocytes produce false-positive biochemical studies but can be used for molecular studies in appropriate cases.

In the neonatal period, the normal to elevated alkaline phosphatase levels present in OI distinguish it from hypophosphatasia. During the school-age period, children with type VI OI have notably elevated serum alkaline phosphatase.

COMPLICATIONS

The morbidity and mortality of OI are cardiopulmonary. Recurrent pneumonias and declining pulmonary function occur in childhood, and cor pulmonale is seen in adults.

Neurologic complications include basilar invagination, brainstem compression, hydrocephalus, and syringohydromyelia. Many children with OI types III and IV have basilar invagination, but brainstem compression is uncommon. Basilar invagination is best detected with spiral CT of the craniocervical junction (Fig. 742.3).

TREATMENT

There is no cure for OI. For severe nonlethal OI, active physical rehabilitation in the early years allows children to attain a higher functional level than orthopedic management alone. Children with OI type I and



Fig. 742.3 Typical feature of basilar invagination shown in the sagittal MRI of an asymptomatic child with type III osteogenesis imperfecta. There is invagination of the odontoid above the Chamberlain line, causing compression and kinking at the pontomedullary junction (arrow).

some with type IV are spontaneous ambulators. Children with types III, IV, V, VI, and XI OI benefit from gait aids and a program of swimming and conditioning. Severely affected patients require a wheelchair for community mobility but can acquire transfer and self-care skills. Teens with OI can require psychologic support with body image issues. Growth hormone improves bone histology in growth-responsive children (usually types I and IV).

Orthopedic management of OI is aimed at fracture management and correction of deformity to enable function. Fractures should be promptly splinted or cast; OI fractures heal well, and cast removal should be aimed at minimizing immobilization osteoporosis. Correction of long-bone deformity requires an osteotomy procedure and placement of an intramedullary rod.

A several-year course of treatment of children with OI with bisphosphonates (IV pamidronate or oral olpadronate or risedronate) confers some benefits. Bisphosphonates decrease bone resorption by osteoclasts; OI patients have increased bone volume that still contains the defective collagen. Bisphosphonates are more beneficial for vertebrae (trabecular bone) than long bones (cortical bone). Treatment for 1-2 years results in increased L1-L4 dual-energy x-ray absorptiometry and, more importantly, improved vertebral compressions and area. However, follow-up of bisphosphonate-treated children has shown that the incidence of scoliosis is unchanged even in children treated early, although there was a modest delay in progression in type III OI. The relative risk of long-bone fractures is modestly decreased by several years of bisphosphonates. However, the material properties of long bones are weakened by prolonged treatment and nonunion after osteotomy is increased. There is no effect of bisphosphonates on mobility scores, muscle strength, or bone pain. Limiting treatment duration to 2-3 years in mid-childhood can maximize the benefits and minimize the detriment to cortical material properties. Benefits appear to persist several years after the treatment interval, and alternation of treatment intervals and drug holidays may be beneficial. Side effects include abnormal long-bone remodeling, increased incidence of fracture nonunion, and osteopetrotic-like brittleness to bone.

Antibodies to sclerostin and TGF- β stimulate osteoblasts to produce bone matrix. They have shown promise in murine models for OI and are currently in trials for children with OI. TGF-beta signaling may be a pathogenic mechanism in OI. Fresolimumab, a TGF-beta neutralizing antibody, treatment in adults with OI type IV demonstrated increases in lumbar spine bone mineral density.

PROGNOSIS

OI is a chronic condition that may limit both life span and functional level. Infants with OI type II usually die within months to 1 year of life. An occasional child with radiographic type II and extreme growth deficiency survives to the teen years. Persons with OI type III have a reduced life span with clusters of mortality from pulmonary causes in early childhood, the teen years, and the 40s. OI types I, IV, and V OI are compatible with a full life span. The oldest reported individuals with type VIII are in their third decade, and some with type XI are in their fourth decade. The long-term prognosis for most recessive types is still emerging, and many adults with OI have not had molecular testing.

Individuals with OI type III are usually wheelchair dependent. With aggressive rehabilitation, they can attain transfer skills and household ambulation. OI type IV children usually attain community ambulation skills either independently or with gait aids.

GENETIC COUNSELING

For autosomal dominant OI, the risk of an affected individual passing the gene to the individual's offspring is 50%. An affected child usually has about the same severity of OI as the parent; however, there is variability of expression, and the child's condition can be either more or less severe than that of the parent. The empirical recurrence risk to an apparently unaffected couple of having a second child with OI is 5-7%; this is the statistical chance that one parent has germline mosaicism. The collagen pathogenic variant in the mosaic parent is present in some

germ cells and may be present in somatic tissues. If a parent is a mosaic carrier, the risk of recurrence may be as high as 50%.

For recessive OI, the recurrence risk is 25% per pregnancy. No known individual with severe nonlethal recessive OI has had a child. For X-linked type XVIII OI, the risk to male offspring of carrier women is generally 50%.

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Section 4

Connective Tissue Disorders

Chapter 743

Marfan Syndrome

Jefferson J. Doyle and Harry C. Dietz III

Marfan syndrome (MFS) is an inherited systemic, connective tissue disorder caused by pathogenic variants in the *FBN1* gene encoding the extracellular matrix (ECM) protein fibrillin-1. It is primarily associated with skeletal, cardiovascular, and ocular pathology. The diagnosis is based on clinical findings, some of which are age dependent.

EPIDEMIOLOGY

The incidence is estimated at 1 in 10,000 live births, and approximately 25% of cases are sporadic. The disorder shows autosomal dominant inheritance, with high penetrance but variable expression. Both inter-familial and intrafamilial clinical variation are common. There is no racial or gender preference.

PATHOGENESIS

MFS is associated with abnormal production, matrix deposition, and/or stability of fibrillin-1, a 350-kd ECM protein that is the major constituent of microfibrils, with prominent disruption of microfibrils and elastic fibers in diseased tissues. The fibrillin-1 (*FBN1*) gene is composed of 65 exons. Linkage analysis has suggested an absence of locus heterogeneity, and the involvement of *FBN1* is demonstrated in >90% of cases, with more than 1,000 disease-causing pathogenic variants identified to date (the majority of which are pathogenic missense variants unique to a given family). With the exception of early-onset and severe presentations of the disease associated with pathogenic variants in exons 26-27 and 31-32, no clear genotype-phenotype correlation has been identified. Given that there is considerable intrafamilial variability, genetic, epigenetic, environmental, or other unidentified factors may influence expression of the disease.

The transforming growth factor beta (TGF- β) family of cytokines influences a diverse repertoire of cellular processes, including cell proliferation, migration, differentiation, survival, and synthetic activity. The TGF- β ligands (TGF- β 1, TGF- β 2, or TGF- β 3) are synthesized as inactive precursor complexes and sequestered by ECM proteins, including fibrillin-1. Mice heterozygous for a pathogenic variant in the fibrillin-1 gene, typical of those that cause MFS in humans, display many of the classic features of MFS, including aortic root aneurysm, which associates with a tissue signature for increased TGF- β signaling, suggesting that pathogenic variants in fibrillin-1 lead to increased TGF- β activation and signaling. Furthermore, pharmacologic antagonism

of TGF- β signaling initiated after the first few weeks of life ameliorates aortic aneurysm in mouse models of MFS, demonstrating that high TGF- β signaling is a cause rather than a consequence of disease progression.

Increased TGF- β signaling has been observed in other tissues in MFS mice, including the developing lung, mitral valve, and skeletal muscle. Treatment of these mice with agents that antagonize TGF- β attenuates or prevents pulmonary emphysema, myxomatous degeneration of the mitral valve, and skeletal muscle myopathy. The prominent role of TGF- β dysregulation in the pathogenesis of MFS was further validated by the discovery and characterization of another related aortic aneurysm syndrome, **Loeys-Dietz syndrome (LDS)**, in which patients have pathogenic variants in the genes encoding positive effectors of TGF- β signaling, including the ligands TGF- β 2 or TGF- β 3, either subunit of the TGF- β receptor (T β RI or T β RII) or the intracellular signaling intermediates SMAD2 or SMAD3. Patients with LDS share many overlapping clinical features with MFS (see the section on “Differential Diagnosis”). This is further supported by data showing that **Shprintzen-Goldberg syndrome (SGS)**, which shows phenotypic overlap with both MFS and LDS, is caused by pathogenic variants in SKI, a known repressor of the TGF- β transcriptional response.

CLINICAL MANIFESTATIONS

MFS is a multisystem disorder, with cardinal manifestations in the skeletal, cardiovascular, and ocular systems.

Skeletal System

Overgrowth of the long bones (**dolichostenomelia**) is often the most obvious manifestation of MFS and may produce a reduced upper segment-to-lower segment ratio (UL/LS) or an arm span-to-height ratio >1.05 times. Abnormal ratios are US/LS <1 for age 0-5 years, US/LS <0.95 for 6-7 years, US/LS <0.9 for 8-9 years, and US/LS <0.85 above age 10 years. Anterior chest deformity is likely the result of excessive rib growth, pushing the sternum either outward (**pectus carinatum**) or inward (**pectus excavatum**). Abnormal curvatures of the spine (most commonly thoracolumbar scoliosis) may also partly result from increased vertebral growth. Other skeletal features include an inward bulging of the acetabulum into the pelvic cavity (**protrusio acetabuli**), flat feet (**pes planus**), and joint hypermobility (Fig. 743.1) or joint contractures. Long and slender fingers in relation to the palm of the hand

(**arachnodactyly**) are generally a subjective finding. The combination of arachnodactyly and hypermobile joints is examined by the Walker-Murdoch or wrist sign, which is positive if there is full overlap of the distal phalanges of the thumb and fifth finger when wrapped around the contralateral wrist (see Fig. 743.1), and the Steinberg or thumb sign, which is present when the distal phalanx of the thumb fully extends beyond the ulnar border of the hand when folded across the palm (see Fig. 743.1). Contracture of the fingers (**camptodactyly**) and elbows is commonly observed. A selection of craniofacial manifestations may be present, including a long narrow skull (dolichocephaly), deeply set eyes (enophthalmos), recessed lower mandible (retrognathia) or small chin (micrognathia), flattening of the midface (**malar hypoplasia**), a high-arching palate, and downward-slanting palpebral fissures (Fig. 743.2).

Cardiovascular System

Thickening of the atrioventricular valves is common and often associated with valvular prolapse. Variable degrees of regurgitation may be present. In children with early-onset and severe MFS, insufficiency of the mitral valve can lead to heart failure, pulmonary hypertension, and death in infancy. This manifestation is the leading cause of morbidity and mortality in young children with the disorder. Supraventricular arrhythmias may be seen in association with mitral valve dysfunction. Ventricular dysrhythmias have also been described in children with MFS, and there is an increased prevalence of prolonged QT interval. Dilated cardiomyopathy occurs with increased prevalence in patients with MFS, most often attributed to volume overload imposed by valve regurgitation. Aortic valve dysfunction is generally a late occurrence and attributed to stretching of the aortic annulus by an expanding aortic root aneurysm.

Aortic aneurysm, dissection, and rupture, principally at the level of the sinuses of Valsalva (also known as the aortic root), remain the most life-threatening manifestations of MFS, prompting lifelong monitoring by echocardiography or other imaging modalities. In severe cases, the aneurysm may be present in utero, but in mild examples it may be absent or never exceed dimensions that require clinical intervention. Aortic dimensions must be interpreted in comparison to age-dependent nomograms. The most important risk factor for aortic dissection is the maximal aortic root size and a positive family history. The characteristic histologic findings from aortas of patients with MFS include cystic medial necrosis of the tunica media and disruption of

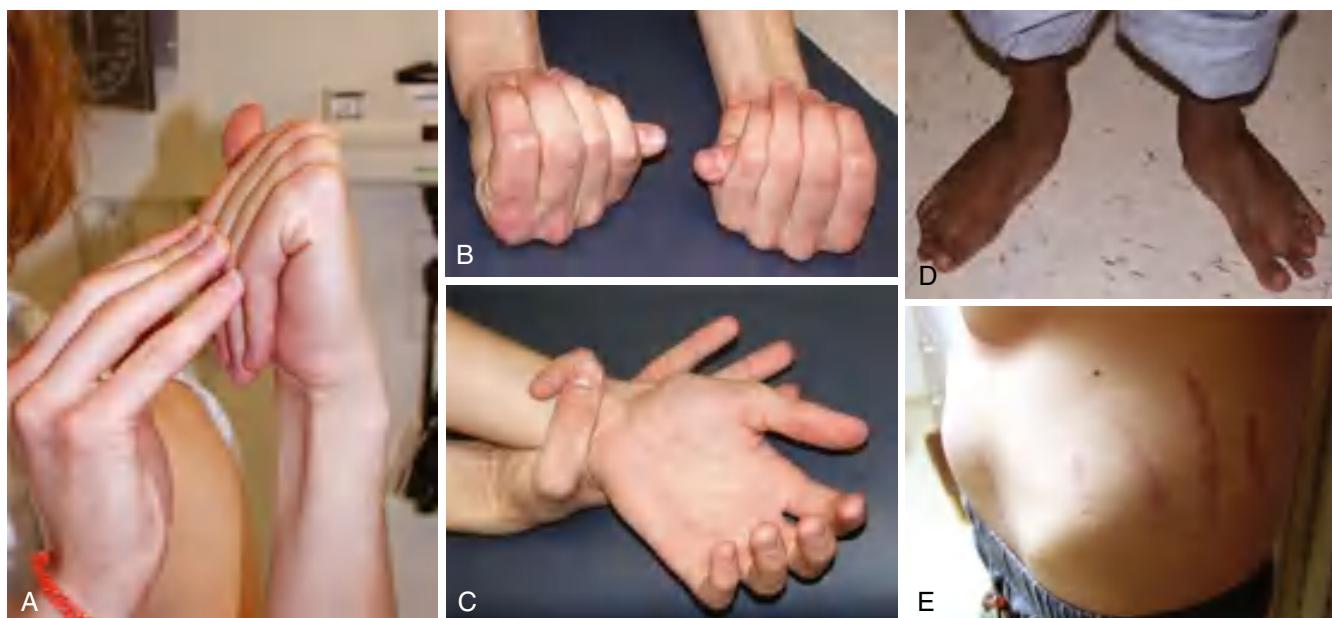


Fig. 743.1 Marfan syndrome. Note the joint laxity (A), Steinberg thumb sign (B), ability to join thumb and fifth finger around the wrist (Walker-Murdoch sign) (C), pes planus (D), and striae over hips and back (E). (From Jones KL, Jones MC, Del Campo M. Smith's Recognizable Patterns of Human Malformation, 8th ed. Philadelphia: Elsevier, 2022; Fig. 2, p. 664.)



Fig. 743.2 Marfan syndrome. Note the long slim limbs, pectus excavatum, narrow face, and reduced elbow extension. (From Jones KL, Jones MC, Del Campo M. Smith's Recognizable Patterns of Human Malformation, 8th ed. Philadelphia: Elsevier; 2022: Fig. 1A, p. 662.)

elastic lamellae. Cystic medial necrosis describes the focal apoptosis and disappearance of vascular smooth muscle cells and elastic fibers from the tunica media of the aortic wall, and subsequent deposition of mucin-like material in the cystic space. These changes produce a thicker, less distensible and stiffer aorta, which is more prone to aortic dissection. Most patients experiencing acute aortic dissection present with classic symptoms, including sudden-onset, severe, tearing chest pain, often radiating into the back. The dissection typically starts at the aortic root and may remain confined to the ascending aorta (type II) or continue into the descending aorta (type I). Acute-onset heart failure may occur if aortic valve function is compromised, and patients may suffer cerebrovascular injury, depending on the involvement of the carotid arteries. Involvement of the coronary arteries may herald sudden cardiac death, secondary to myocardial infarction or rupture into the pericardial sac with subsequent pericardial tamponade. Chronic aortic dissection usually occurs more insidiously, often without chest pain. Dilatation of the main pulmonary artery is common but does not typically cause any clinical sequelae. Enlargement of the descending thoracic or abdominal aorta can also occur, although relatively rarely.

Ocular System

Dislocation of the ocular lens (**ectopia lentis**, EL) occurs in around 60–70% of patients, although it is not unique to the disorder. Other ocular manifestations include early and severe myopia, thin and flat cornea, increased axial length of the globe, and iris dilator muscle hypoplasia, which results in poor dilation (miosis). Patients are also predisposed to retinal detachment, early cataracts, glaucoma, strabismus, and amblyopia.

Table 743.1 Diagnostic Criteria for Marfan Syndrome

IN THE ABSENCE OF A FAMILY HISTORY OF MFS, A DIAGNOSIS CAN BE ESTABLISHED IN FOUR DISTINCT SCENARIOS:

1. Aortic root z score ≥ 2 AND ectopia lentis*
2. Aortic root z score ≥ 2 AND a bona fide *FBN1* pathogenic variant (see Table 743.2)
3. Aortic root z score ≥ 2 AND a systemic score $\geq 7^*$ (see Table 743.3)
4. Ectopia lentis AND a bona fide *FBN1* pathogenic variant known to cause aortic disease

IN THE PRESENCE OF A FAMILY HISTORY OF MFS, A DIAGNOSIS CAN BE ESTABLISHED IN THE PRESENCE OF:

1. Ectopia lentis
2. A systemic score $\geq 7^*$
3. Aortic root z score ≥ 2 if older than 20 years or ≥ 3 if younger than 20 years*

IN THE ABSENCE OF A FAMILY HISTORY OF MFS, ALTERNATIVE DIAGNOSES INCLUDE:

1. Ectopia lentis \pm systemic score AND *FBN1* pathogenic variant not known to associate with aortic aneurysm or no *FBN1* pathogenic variant = Ectopia lentis syndrome
2. Aortic root z score < 2 AND a systemic score ≥ 5 (with at least one skeletal feature) without ectopia lentis = MASS phenotype
3. Mitral valve prolapse AND aortic root z score < 2 AND a systemic score < 5 without ectopia lentis = Mitral valve prolapse syndrome

*Denotes caveat that features suggestive of an alternative diagnosis must be excluded and appropriate alternative molecular testing should be performed. Other syndromes include Shprintzen-Goldberg, Loeys-Dietz, or vascular Ehlers Danlos (see Table 743.4 for genes).

Other Systems

There is an increased incidence of pulmonary disease in MFS; progressive anterior chest deformity or thoracic scoliosis may contribute to a restrictive pattern of lung disease. Furthermore, a widening of the distal airspaces predisposes patients to spontaneous pneumothorax, which occurs in up to 15% of patients. Assessment of pulmonary volumes and function should account for long-bone overgrowth affecting the lower extremities, which can lead to a reduction in the normalized forced vital capacity and total lung capacity. If normalized to thoracic size or sitting height, pulmonary function testing is often normal in patients with the disorder.

MFS patients typically have normal skin texture and elasticity. The most common skin finding is stretch marks—pinkish, scarlike lesions that later become white (**striae atrophicae**), which occur in about one third of patients (Fig. 743.1). These may occur in the absence of obesity, rapid gain in muscle mass, or pregnancy, and at sites not associated with increased skin distention (i.e., the anterior shoulder or lower back). Another common manifestation is congenital or acquired inguinal hernia. There is also an increased risk of surgical and recurrent hernias in the Marfan population.

Widening of the dural sac or root sleeves (dural ectasia) is present in 63–92% of MFS patients. Although dural ectasia can result in lumbar back pain, it is often asymptomatic and should be assessed by lumbo-sacral imaging with CT or MRI.

DIAGNOSIS

Given the complexity of the clinical examination in MFS and the relevant differential diagnoses, evaluation should be coordinated by a professional with extensive experience, such as a geneticist, cardiologist, or ophthalmologist. The diagnosis is based on a defined set of clinical criteria drawn up by an international panel of experts (the revised Ghent nosology for the MFS; Table 743.1).

In the absence of a conclusive family history of MFS, the diagnosis can be established in four distinct scenarios:

1. The presence of either aortic root dilatation when standardized to age and body size (an aortic root z score ≥ 2) or aortic dissection combined with ectopia lentis allows for the unequivocal diagnosis of MFS, irrespective of the presence or absence of any systemic features (see Table 743.1), except when these are indicative of an alternative diagnosis.

Table 743.2 Criteria for Causal *FBN1* Pathogenic Variant

- Pathogenic variant previously shown to segregate in a Marfan family
- Any one of the following de novo pathogenic variants (with proven parentage and absence of disease in parents):
 - Nonsense pathogenic variant
 - In-frame and out-of-frame deletion/insertion
 - Splice site pathogenic variants affecting canonical splice sequence or shown to alter splicing on mRNA/cDNA level
 - Missense pathogenic variant affecting/creating cysteine residues
 - Missense pathogenic variant affecting conserved residues of the EGF consensus sequence ((D/N)X(D/N)(E/Q)Xm(D/N) Xn(Y/F) with *m* and *n* representing variable number of residues; D aspartic acid, N asparagine, E glutamic acid, Q glutamine, Y tyrosine, F phenylalanine)
 - Other missense pathogenic variants: segregation in family if possible AND absence in 400 ethnically matched control chromosomes; if no family history, absence in 400 ethnically matched control chromosomes
 - Linkage of haplotype for *n* ≥ 6 meioses to the *FBN1* locus

From Loeys BL, Dietz HC, Braverman AC, et al. The revised Ghent nosology for the Marfan syndrome. *J Med Genet*. 2010;47:476–485.

Table 743.3 Scoring of Systemic Features in Points

- Wrist AND thumb sign = 3 (wrist OR thumb sign = 1)
- Pectus carinatum deformity = 2 (pectus excavatum or chest asymmetry = 1)
- Hind foot deformity = 2 (plain pes planus = 1)
- Pneumothorax = 2
- Dural ectasia = 2
- Protrusion acetabuli = 2
- Reduced US/LS AND increased arm/height AND no severe scoliosis = 1
- Scoliosis or thoracolumbar kyphosis = 1
- Reduced elbow extension = 1
- Facial features (3/5) = 1 (dolichocephaly, enophthalmos, down-slanting palpebral fissures, midface hypoplasia, retrognathia)
- Skin striae = 1
- Myopia >3 diopters = 1
- Mitral valve prolapse (all types) = 1

Maximum total: 20 points; score ≥7 indicates systemic involvement.
US/LS, Upper segment/lower segment ratio.

2. The presence of aortic root dilatation (*z* score ≥2) or aortic dissection and the identification of a bona fide *FBN1* pathogenic variant (Table 743.2) are sufficient to establish the diagnosis even if ectopia lentis is absent.
3. When aortic root dilatation (an aortic root *z* score ≥2) or aortic dissection is present, but ectopia lentis is absent and the *FBN1* status is either unknown or negative, the diagnosis may be confirmed by the presence of sufficient systemic findings (a systemic score ≥7 points; Table 743.3). However, features suggestive of an alternative diagnosis must be excluded, and the appropriate alternative molecular testing should be performed.
4. In the presence of ectopia lentis, but absence of aortic root dilatation or aortic dissection, an *FBN1* pathogenic variant, which has previously been associated with aortic disease, is required before the diagnosis can be made. If the *FBN1* pathogenic variant is not unequivocally associated with cardiovascular disease in either a related or unrelated proband, the patient should be classified as “isolated ectopia lentis syndrome” (see the section on “Differential Diagnosis”). Despite these diagnostic criteria, on occasion sporadic cases in individuals <20 years old may not fit in one of the four proposed scenarios detailed above. If insufficient systemic features (systemic score <7) and/or borderline aortic root measurements (*z* score <3) are present

without documented evidence of a bona fide *FBN1* pathogenic variant, the term “nonspecific connective tissue disorder” is recommended. In those instances in which an *FBN1* pathogenic variant is identified, the term *potential MFS* should be used instead.

In an individual with a positive family history of MFS (in which a family member has been independently diagnosed using the previously described criteria), the diagnosis can be established in the presence of:

1. Ectopia lentis
2. A systemic score ≥7 points (see Table 743.3)
3. Aortic root dilatation with *z* score ≥2 in adults (≥20 years old) or *z* score ≥3 in individuals <20 years old

In the case of scenarios 2 and 3, previously, features suggestive of an alternative diagnosis must again be excluded and appropriate alternative molecular testing should be performed.

DIFFERENTIAL DIAGNOSIS

The differential diagnosis of MFS includes disorders with aortic aneurysm (LDS, familial thoracic aortic aneurysm syndrome, and SGS), ectopia lentis (ectopia lentis syndrome, Weil-Marchesani syndrome, and homocystinuria), or systemic manifestations of MFS (congenital contractual arachnodactyly [CCA] and mitral valve, aorta, skin, skeletal [MASS] phenotype); Table 743.4.

Aortic Aneurysm Syndromes

LDS is a systemic connective tissue disorder characterized by the triad of arterial tortuosity and aggressive aneurysm disease, hypertelorism, and bifid uvula or cleft palate, as well as many of the craniofacial and skeletal features found in MFS. Distinction between MFS and LDS is important because aneurysms tend to dissect at younger ages and smaller dimensions in LDS patients, necessitating more aggressive management. LDS was originally classified into type 1 or type 2, depending on whether the pathogenic variant is present in the *TGFBRI* or *TGFBRII* gene, which encode the type 1 or type 2 TGF-β receptor subunits, respectively. LDS type 3 is caused by heterozygous pathogenic variants in the gene encoding the TGF-β-dependent intracellular signaling molecule SMAD3. LDS type 4 is caused by heterozygous pathogenic variants in the extracellular TGF-β receptor ligand TGF-β2, whereas LDS type 5 is caused by heterozygous pathogenic variants in the extracellular TGF-β receptor ligand TGF-β3. LDS type 6 is caused by heterozygous pathogenic variants in the gene encoding the TGF-β-dependent intracellular signaling molecule SMAD2. As a general rule, the severity of disease associated with the different forms of LDS can be summarized: LDS1 = LDS2 > LDS3 > LDS4 = LDS5 > LDS6. There are exceptions to this rule, mandating careful monitoring of all patients with LDS. Notably, there can be wide clinical variation within each subtype, including between family members harboring the identical pathogenic variant.

Like MFS, **familial thoracic aortic aneurysm syndrome** segregates as an autosomal dominant trait characterized by aortic root aneurysm and dissection. However, other systemic manifestations of MFS are typically absent, and the disorder has reduced penetrance. Disease-causing heterozygous pathogenic variants have been identified in several genes with roles in the vascular smooth muscle contractile apparatus, including *MYH11*, *ACTA2*, and *MYLK*, which encode smooth muscle myosin heavy chain 11, vascular smooth muscle α-actin, and myosin light chain kinase. However, these genes account for only a fraction of cases of *nonsyndromic* familial thoracic aortic aneurysm. In most cases, the management principles that have been generated for MFS have proved effective for this form of familial aortic aneurysm.

SGS is a systemic connective tissue disorder that includes virtually all the craniofacial, skeletal, skin, and cardiovascular manifestations of MFS and LDS, with the additional findings of developmental delay and severe skeletal muscle hypotonia. Most cases are caused by heterozygous pathogenic variants in the *SKI* gene, which encodes an intracellular repressor of TGF-β signaling. Vascular involvement tends to be less prevalent and less severe when compared with MFS or LDS.

Table 743.4 Differential Diagnosis of Marfan Syndrome

DIFFERENTIAL DIAGNOSIS (GENES)	CARDIAC FEATURES	VASCULAR FEATURES	SYSTEMIC FEATURES
AORTIC ANEURYSM SYNDROMES			
Loeys-Dietz syndromes (types I-V) (OMIM: 609192) <i>TGFBR1, TGFBR2, SMAD3, TGFβ2, TGFβ3</i>	<ul style="list-style-type: none"> • Patent ductus arteriosus • Atrial septal defect • Bicuspid aortic valve 	<ul style="list-style-type: none"> • Aortic root aneurysm • Arterial tortuosity • Widespread aneurysms • Vascular dissection at relatively young ages and small aortic dimensions 	<ul style="list-style-type: none"> • Hypertelorism • Cleft palate • Broad or bifid uvula • Craniostenosis • Midface hypoplasia • Blue sclerae • Arachnodactyly • Pectus deformity • Scoliosis • Joint hypermobility • Pes planus • Rarely easy bruising • Dystrophic scars • Translucent skin • Rarely developmental delay
Familial thoracic aortic aneurysm (OMIM: 132900) <i>TGFBR2, ACTA2, others</i>	<ul style="list-style-type: none"> • Generally none • Rare forms with patent ductus arteriosus 	<ul style="list-style-type: none"> • Aortic root aneurysm • Ascending aortic aneurysm 	<ul style="list-style-type: none"> • Generally none • Rarely livedo reticularis and iris flocculi
Shprintzen-Goldberg syndrome (OMIM: 182212) <i>SKI, unknown others</i>	None	Aortic root aneurysm	<ul style="list-style-type: none"> • Hypertelorism • Craniostenosis • Arched palate • Arachnodactyly • Pectus deformity • Scoliosis • Joint hypermobility • Developmental delay
Bicuspid aortic valve with aortic aneurysm (OMIM: 109730) <i>ACTA2</i>	Bicuspid aortic valve	<ul style="list-style-type: none"> • Aortic root aneurysm • Ascending aortic aneurysm 	
Ehlers-Danlos syndrome, type IV (OMIM: 130050) <i>COL3A1</i>	Mitral valve prolapse	<ul style="list-style-type: none"> • Aneurysm and rupture of any medium to large muscular artery • No predisposition for aortic root enlargement 	<ul style="list-style-type: none"> • Joint hypermobility • Atrophic scars • Translucent skin • Easy bruising • Hernias • Rupture of hollow organs
ECTOPIA LENTIS SYNDROMES			
Familial ectopia lentis (OMIM: 129600) <i>FBN1, LTBP2, ADAMTSL4</i>	None	None	Nonspecific skeletal features
Homocystinuria (OMIM: 236200) <i>CBS</i>	Mitral valve prolapse	Intravascular thrombosis	<ul style="list-style-type: none"> • Tall stature • Ectopia lentis • Long-bone overgrowth • Developmental delay
SYNDROMES WITH SYSTEMIC MANIFESTATIONS OF MFS			
MASS (mitral valve, aorta, skeleton, skin) phenotype (OMIM: 604308) <i>FBN1</i>	Mitral valve prolapse	Borderline or nonprogressive	<ul style="list-style-type: none"> • Nonspecific skin and skeletal findings • Myopia

Ectopia Lentis Syndromes

Both **ectopia lentis syndrome** and **Weill-Marchesani syndrome (WMS)** may also be caused by heterozygous pathogenic variants in *FBN1*. Compound heterozygous or homozygous pathogenic variants at a second locus, *ADAMTSL4* cause ectopia lentis syndrome associated with slightly younger age at diagnosis. Interestingly, some *FBN1* pathogenic variants can be associated with classic MFS, ectopia lentis syndrome, and ectopia lentis combined with skin, but not cardiovascular, manifestations of MFS, suggesting that these presentations are part of a spectrum of clinical features of the same disease, and highlighting the potential contribution of genetic modifiers of disease.

WMS is a systemic connective tissue disorder characterized by skin, skeletal, and ocular abnormalities, including

microspherophakia, ectopia lentis, and myopia. Features inconsistent with the diagnosis of MFS include short stature and brachydactyly. In addition to *FBN1* pathogenic variants (type 2), the syndrome may be caused by biallelic pathogenic variants in *ADAMTS10* (type 1) or in *LTBP2* (type 3), which encode ADAM metallopeptidase with thrombospondin type 1 motif 10 and latent TGF- β binding protein 2, respectively.

Homocystinuria is a metabolic disorder caused by homozygous or compound heterozygous pathogenic variants in the gene encoding cystathione β -synthase, which leads to increases in both homocysteine and methionine. The clinical features of untreated homocystinuria include ectopia lentis and skeletal abnormalities resembling MFS. However, in contrast to MFS, affected persons often suffer from developmental delay, a predisposition to

thromboembolic events, and a high incidence of coronary artery disease. Patients with homocystinuria are not at increased risk for aortic aneurysm.

Syndromes with Systemic Manifestations of MFS

Congenital contractual arachnodactyly (CCA) is a connective tissue disorder caused by heterozygous pathogenic variants in the gene encoding fibrillin-2 (*FBN2*). There are a number of clinical features overlapping with MFS, including dolichostenomelia, anterior chest deformity, scoliosis, joint contractures, and arachnodactyly, as well as some craniofacial malformations, including highly arched palate and retrognathia. In addition, both may suffer from severe cardiovascular abnormalities leading to premature death, but the specific cardiac anomalies are different; valvular insufficiency and aortic root dilation are common with MFS, whereas congenital heart defects are more common in CCA. Patients with CCA also suffer from crumpled auricular helices (a hallmark of this condition).

Many patients referred for possible MFS are found to have evidence of a systemic connective tissue disorder, including long limbs, deformity of the thoracic cage, striae atrophicae, mitral valve prolapse, and borderline but nonprogressive dilatation of the aortic root, but do not meet diagnostic criteria for MFS. This constellation of features is referred to by the acronym **MASS phenotype**, emphasizing the *mitral, aortic, skin, and skeletal* manifestations. The MASS phenotype can segregate in large pedigrees and remain stable over time. The diagnosis is particularly challenging in the context of a young, sporadic patient in whom careful follow-up is needed to distinguish MASS phenotype from early MFS. Familial mitral valve prolapse syndrome can also be caused by pathogenic variants in the gene encoding fibrillin-1 and include subdiagnostic systemic manifestations.

LABORATORY FINDINGS

Laboratory studies should document a negative urinary cyanide nitroprusside test or specific amino acid studies to exclude cystathione β -synthase deficiency (homocystinuria). Although it is estimated that most, if not all, people with classic MFS have a *FBN1* pathogenic variant, the large size of this gene and the extreme allelic heterogeneity in MFS have frustrated efficient molecular diagnosis. The yield of pathogenic variant screening varies based on technique and clinical presentation. It remains unclear whether the “missing” pathogenic variants are simply atypical in character or location within *FBN1* or located in another gene. Other differential diagnoses, such as MASS phenotype, EL, and WMS have been associated with pathogenic variants in the *FBN1* gene. Furthermore, it is often difficult or impossible to predict the phenotype from the nature or location of a *FBN1* pathogenic variant in MFS. Hence molecular genetic techniques can contribute to the diagnosis, but they do not substitute for comprehensive clinical evaluation and follow-up. Consequently, the absence or presence of a *FBN1* pathogenic variant is not sufficient to exclude or establish the diagnosis, respectively.

MANAGEMENT

Management focuses on preventing complications and genetic counseling. Referral to a multidisciplinary center where a geneticist with experience in MFS works in concert with subspecialists to coordinate a rational approach to monitoring and treatment is advisable, given the complex nature of some patients' disease. Yearly evaluations for cardiovascular disease, scoliosis, or ophthalmologic problems are imperative.

CURRENT THERAPIES

Most therapies currently available or under investigation aim to diminish cardiovascular complications, which can be categorized into activity restrictions, aortic surgery, endocarditis prophylaxis, and current pharmacologic approaches.

Activity Restrictions

Physical therapy can improve cardiovascular performance, neuromuscular tone, and psychosocial health, and so aerobic exertion in moderation is recommended. However, strenuous physical exertion, competitive or contact sports, and particularly isometric activities such as weightlifting, which invoke a Valsalva maneuver, should be avoided.

Aortic Surgery

Surgical outcome is more favorable if undertaken on an elective rather than an urgent or emergent basis (mortality of 1.5% vs 2.6% and 11.7%, respectively). Therefore aortic surgery should be recommended for adult patients when their aortic root diameter approaches 50 mm, and early intervention should be considered for those with a rapid rate of enlargement (>5-10 mm/yr) or a family history of early aortic dissection. There are no definitive criteria guiding the timing of surgery in children in whom dissection is extremely rare, irrespective of aortic size. This has prompted many centers to adopt the adult criterion of 50 mm, although early surgery may be undertaken in the presence of a rapid rate of growth (>10 mm/yr) or the emergence of significant aortic regurgitation. Preserving the native aortic valve at the time of repair is desirable to avoid the need for lifelong anticoagulation. Mitral valve repair or replacement is advised for severe mitral valve regurgitation with associated symptoms or progressive left ventricular dilatation or dysfunction.

Pregnancy

There is higher risk of aortic dissection during pregnancy and particularly in the early postpartum period in women with MFS. However, improved awareness and data have indicated the risk is low in patients with an aortic root diameter <40 mm. Prophylactic aortic root replacement can minimize the risk of aortic dissection and death in women with MFS who wish to become pregnant, but the risk of more distal ascending or descending aortic dissection would not be modified by this intervention. Work in mouse models of MFS and other vascular connective tissue disorders has associated postpartum aortic rupture with lactation and specifically the activity of the hormone oxytocin. This complication can be diminished or even avoided in some mouse models by avoiding lactation through pup removal or a pharmacologic antagonist of the oxytocin receptor. Although more work needs to be done in this area, we discuss the potential negative implications of lactation with women with MFS that choose to become pregnant and are deemed to be at particularly high risk based on the personal or family history.

Endocarditis Prophylaxis

The Professional Advisory Board of the National Marfan Foundation believes that patients with MFS should continue to receive prophylaxis for bacterial endocarditis, in part because it remains unknown, but possible, that the myxomatous valves typical of MFS are a preferred substrate for bacterial infection.

Current Pharmacologic Approaches

β -Blockers

β -Adrenergic receptor blockers have historically been considered the standard of care in MFS, and multiple small observational studies have suggested there is a protective effect on aortic root growth, with the dose typically titrated to achieve a heart rate <100 beats/min during submaximal exercise. Given the putative role of hemodynamic stress in aortic dilatation and aortic dissection in MFS, these effects are attributed to the negative inotropic and chronotropic effects of β -blockade.

Angiotensin II Receptor Type 1 Blockers

There is extensive evidence linking angiotensin II signaling to TGF- β activation and signaling. In a mouse model of MFS, the angiotensin II receptor type 1 blocker (ARB) losartan was shown to completely prevent pathologic aortic root growth and to normalize both aortic wall thickness and architecture, findings that were absent in placebo-treated and propranolol-treated mice. These data suggest the potential for productive aortic wall remodeling in MFS after TGF- β inhibition.

In support of its relevance to humans, a retrospective study assessing the effect of ARBs in a small cohort of pediatric patients with MFS who had severe aortic root enlargement despite previous alternative medical therapy, showed that ARBs significantly slowed the rate of aortic root and sinotubular junction dilatation (both of which occur in MFS), whereas the distal ascending aorta (which does not normally become dilated in MFS) remained unaffected. Further evidence of a beneficial effect from losartan therapy has been provided by three prospective clinical trials demonstrating that losartan treatment alone or in combination with β -blockade slowed the progression of aortic root dilation in patients with MFS.

A comparison clinical trial assessing the therapeutic benefit of losartan versus atenolol in patients with MFS concluded that both drugs provided significant protection against aortic growth, with no significant difference in therapeutic effect between the two drugs despite the use of conventional dose losartan (FDA-approved dose for hypertension) and an atypically high dose of atenolol (average dose of atenolol was 1.5 times and the maximum dose was 2 times the FDA approved upper limit for the treatment of hypertension). Both treatment arms in this trial showed a very slow rate of aortic root growth and a significant decline in aortic root z score over time, a performance superior to that observed in untreated Marfan patients or in patients treated with conventional dose atenolol (1–2 mg/kg/day). These data strongly suggest that both modalities have therapeutic roles in patients with MFS.

Additional prospective studies have demonstrated therapeutic benefit of ARBs. A meta-analysis integrating seven randomized prospective trials and over 1,500 patients concluded that ARBs are both efficacious and safe in MFS, either when used alone (in comparison to placebo) or in combination with β -blockers (in comparison to β -blockers alone). An 8-year follow-up of a Dutch study exploring the use of ARBs in adults with MFS suggested that this treatment not only suppressed pathologic aortic growth but also positively influenced important patient outcomes, including risk of surgery, aortic dissection, and all-cause mortality.

PROGNOSIS

The major cause of mortality is aortic root dilatation, dissection, and rupture, with the majority of fatal events occurring in the third and fourth decades of life. A reevaluation of life expectancy in MFS suggested that early diagnosis and refined medical and surgical management has greatly improved the prognosis for patients with the condition. Nevertheless, MFS continues to be associated with significant morbidity, and selected subgroups are refractory to therapy and continue to show early mortality. In a review of 54 patients diagnosed during infancy, 89% had serious cardiac pathology, and cardiac disease was progressive despite standard care (22% died during childhood, 16% before age 1 year). In the classic form of MFS, it is estimated that more than 90% of individuals will have a cardiovascular event during their lifetime, placing both physical and mental stresses on patients and their families. Awareness of these issues and referral for support services can facilitate a positive perspective toward the condition.

GENETIC COUNSELING

The heritable nature of MFS makes recurrence risk (genetic) counseling mandatory. Fathers of these sporadic cases are, on average, 7–10 years older than fathers in the general population. This paternal age effect suggests that these cases represent new dominant pathogenic variants with minimal recurrence risk to additional future offspring of the normal parents. Owing to rare reports of gonadal mosaicism in a phenotypically normal parent, the recurrence risk for parents of a sporadic case can be reported as low but not zero. Each child of an affected parent, however, has a 50% risk of inheriting the MFS pathogenic variant and thus being affected. Recurrence risk counseling is best accomplished by professionals with expertise in the issues surrounding the disorder.

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Chapter 744

Ehlers-Danlos Syndrome

Donald Basel

Ehlers-Danlos syndrome (EDS) is a heterogeneous group of heritable connective tissue disorders that are grouped into three broad pathoetiological categories and more specifically divided into fourteen subtypes (Table 744.1). Affected individuals are considered to have an overlapping phenotype of abnormally soft, extensible skin, which often heals poorly, in association with joint hypermobility and occasional instability believed to be rooted in a disruption of normal collagen function (Tables 744.2 and 744.3). All organ systems contain connective tissue elements, and many of these elements are involved in supporting the function of feedback receptors such as mechanoreceptors in lumen or vessel walls or stretch receptors in tendons. The myriad of symptoms, variability of expression, modes of inheritance, and unique phenotypic elements distinguish the subtypes from one another while establishing their common origins. The hypermobility type (hEDS) is the most common form and has no clear molecular etiology.

The connective tissue matrix is complex (Fig. 744.1), and the interplay of cells, collagen and elastin fibers, proteins, and cell signaling molecules remains poorly understood. However, dysfunction at both structural and functional levels more than likely explains the complex medical associations typically encountered in this population, with complaints ranging from joint instability and tissue fragility to chronic pain, autonomic dysfunction, and chronic fatigue (see Table 744.3).

CLASSIFICATION OF THE SIX MOST COMMON SUBTYPES OF EHLERS-DANLOS SYNDROME

Classic (Genes: COL5a1, COL5a2, COL1a1; Previously EDS Type I—Gravis, EDS Type II—Mitis)

Classic EDS is the second most common form of EDS and is an autosomal dominant connective tissue disorder characterized by skin hyperelasticity (Fig. 744.2), widened atrophic scars (skin fragility), and joint hypermobility. Other features include easy bruising, which is often associated with hemosiderin staining of the tissues (particularly over regions exposed to frequent trauma, like the shins). The skin is “velvet” to the touch and is particularly fragile, with minor lacerations forming gaping wounds that leave broad, atrophic, papryaceous (“cigarette paper”) scars (Fig. 744.3; see also Table 744.2). Additional cutaneous manifestations include molluscoid pseudotumors over pressure points from accumulations of connective tissue and piezogenic papules (Fig. 744.4). Joints are hypermobile, often with joint instability (Fig. 744.5). Scoliosis frequently presents in adolescence, and mitral valve prolapse is common. Life expectancy is generally not reduced, although rare rupture of large arteries has been reported. Similar noncutaneous nonarticular comorbidities, as seen in hypermobile EDS, are found, in particular pain and gastrointestinal dysfunction (see Table 744.3). Premature birth caused by rupture of membranes of an affected offspring is not uncommon. The diagnosis is made by clinical findings and sequencing of COL5A1 and COL5A2 genes.

Hypermobility (Cause Unknown, Previously EDS Type III)

Hypermobile EDS (hEDS) is the most prevalent form of EDS with an estimated population frequency of between 0.75–3%. It is an autosomal dominant disorder, but the causative molecular pathoetiology remains elusive. Fewer than 3% of patients with a hEDS phenotype are associated with heterozygous tenascin X gene loss of function, and likewise, only a minority of cases are linked to other findings, such as the association with mosaic type 1 collagen

Table 744.1 Classification of Ehlers-Danlos Syndrome

Type	Gene	Skin Findings	Joint Changes	Inheritance	Other Comments
Classic	<i>COL5A1, COL5A2</i> (usually haploinsufficiency)	Hyperextensibility, bruising, velvety skin, widened atrophic scars, molluscoid pseudotumors, spheroids	Hypermobility and its complications, joint dislocations	AD	Mitral valve prolapse, hernias
	<i>COL1A1</i> Specific pathogenic variant; c.934C>T			AD	Blue sclerae, short stature, osteopenia/fractures; may have late arterial rupture
CLASSIC VARIANTS					
Cardiac valvular	Biallelic loss of function for <i>COL1A2</i>	Classic EDS features		AR	Severe cardiac valve issues as adult
Periodontal	<i>C1R</i> <i>C1S</i>	Can have classic EDS features	Can have hypermobility	AD	Periodontitis, marfanoid habitus, prominent eyes, short philtrum
Classic-like	<i>TNXB</i>	Hyperextensibility, marked hypermobility, severe bruising, velvety skin, no scarring tendency	Hypermobility	AR	Parents (especially mothers) with one <i>TNXB</i> pathogenic variant; can have joint hypermobility
	<i>AEBP1</i>	Joint hypermobility, extensible and redundant skin, abnormal scarring	Hypermobility	AR	Biallelic loss of function variants. Highly variable.
Hypermobility	Unknown	Mild hyperextensibility, scarring, textural change	Hypermobility, chronic joint pain, recurrent dislocations	AD	Sometimes confused with joint hypermobility syndrome
Vascular	<i>COL3A1</i> Rare variants in <i>COL1A1</i>	Thin, translucent skin, bruising, early varicosities, acrogeria	Small joint hypermobility	AD	Abnormal type III collagen secretion; rupture of bowel, uterus, arteries; typical facies; pneumothorax
Kyphoscoliosis	<i>PLOD</i> (deficient lysyl hydroxylase) <i>FKBP14</i>	Soft, hyperextensible skin, bruising, atrophic scars	Hypermobility	AR	Severe congenital muscle hypotonia that improves a little in childhood; congenital kyphoscoliosis, scleral fragility and rupture, marfanoid habitus, osteopenia, sensorineural hearing loss
VARIANTS WITH KYPHOSCOLIOSIS					
Spondylocheiro-dysplastic form	<i>SLC39A13</i> , which encodes the ZIP13 zinc transporter <i>B4GALT7</i> or <i>B3GALT6</i> , encoding galactosyltransferase I or II, key enzymes in GAG synthesis	Similar to kyphoscoliotic form		AR	Spondyloepimetaphyseal dysplasia; can have bone fragility and severe progressive kyphoscoliosis without congenital hypotonia; moderate short stature, loose facial skin, wrinkled palms with thenar and hypothenar atrophy, blue sclerae, curly hair, alopecia
Brittle cornea syndrome	<i>ZNF469</i> or <i>PRDM5</i>	Skin hyperextensibility	Joint hypermobility	AR	Kyphoscoliosis; characteristic thin, brittle cornea, ocular fragility, blue sclera, keratoconus
Musculocontractural	<i>CHST14</i> (encoding dermatan 4-O-sulfotransferase) <i>DSE</i> (encoding dermatan sulfate epimerase)	Fragile, hyperextensible skin with atrophic scars and delayed wound healing	Hypermobility	AR	Progressive kyphoscoliosis; adducted thumbs in infancy, clubfoot, arachnodactyly, contractures, characteristic facial features, hemorrhagic diathesis
Myopathic	<i>COL12A1</i>	Soft, hyperextensible	Hypermobile small joints, large joint contractures (hip, knees, elbows)	AD or AR	Characterized by muscle hypotonia and weakness

Table 744.1 Classification of Ehlers-Danlos Syndrome—cont'd

TYPE	GENE	SKIN FINDINGS	JOINT CHANGES	INHERITANCE	OTHER COMMENTS
Arthrochalasis	Exon 6 deletion of COL1A1 or COL1A2	Hyperextensible, soft skin with or without abnormal scarring	Marked hypermobility with recurrent subluxations	AD	Congenital hip dislocation, arthrochalasis, multiplex congenita, short stature
Dermatosparaxis	Type I collagen N-peptidase ADAMTS2	Severe fragility, sagging, redundant skin		AR	Also occurs in cattle

AD, Autosomal dominant; AR, autosomal recessive; EDS, Ehlers–Danlos syndrome; GAG, glycosaminoglycan.

From Malfait F, Francomano C, Byers P, et al. The 2017 International Classification of the Ehlers–Danlos syndromes. *Am J Med Genet C Semin Med Genet*. 2017;175(1):8–26.**Table 744.2** Common and Uncommon Features of Classic Ehlers-Danlos Syndrome

SKIN
Hyperextensible
Velvety
Fragile, thin, poor tensile strength
Atopic scarring ("cigarette-paper" scars)
Striae
Bruising and bleeding (hemosiderin staining of skin)
Piezogenic papules, subcutaneous sphenoids
Wound dehiscence/incisional hernia
MUSCULOSKELETAL/JOINTS
Hypermobile ± joint dislocations
Pes planus
Chronic musculoskeletal pain, sprains
Late walking, hypotonia
OTHER ORGAN INVOLVEMENT
Chiari type I malformation
Gastrointestinal (nausea, reflux, constipation)
Umbilical hernia
Hiatal hernia
Mitral valve prolapse
Aortic root dilation
CSF leak/headache
Pelvic organ prolapse
Premature rupture of fetal membranes
Cervical incompetence
Stress incontinence
Hyperkyphosis
Scoliosis
High arched palate
Femur anteversion ("W" sitting position)
Hollow organ rupture, diverticula
Occipitoatlantoaxial hypermobility

defects. There are currently no diagnostic biomarkers, and the inter- and intrafamilial variation has clouded the ability to clearly define large study populations with sufficient phenotypic alignment. An editorial highlighted the impact of sex hormones and associations of certain symptom complexes to environmental exposures or "trigger events," which begs the question of a more complex gene-environment or epigenetic influence.

The primary clinical finding in hEDS is generalized joint hypermobility with less prominent skin manifestations. There is inconsistency in the literature as to what defines hypermobility, but generally a score of ≥ 6 on the Beighton hypermobility scale (Fig. 744.6, Table 744.4) would qualify as hypermobility in prepubertal children and adolescents, ≥ 5 for postpubertal individuals up to the age of 50, and ≥ 4 for all adults beyond the age of 50. Children < 6 years of age generally tend toward a hypermobile state, and the Beighton score may not be a reliable indicator of connective tissue laxity in these children (Table 744.5). Joint instability with frequent

Table 744.3 Associated Features in Ehlers-Danlos/Hypermobility Spectrum Disorders**AUTONOMIC AND NEUROLOGIC DYSFUNCTION**

Postural orthostatic tachycardia syndrome (POTS)
Dizziness
Palpitations
Gastroparesis
Diarrhea
Constipation
Sleep dysfunction
Chronic fatigue
Headache (migraine, new daily headache)
Urinary stress incontinence
Somatosensory amplification
Irritable bowel syndrome
Neuropathic pain

MUSCULOSKELETAL PAIN

Chronic regional pain syndrome
Fibromyalgia

dislocations is common but not universal; joints are predisposed to osteoarthritis in adults.

Patients with hEDS have significant nonarticular comorbidities associated with functional disorders. These present as complex pain, dysautonomia, chronic fatigue, anxiety, and sleep dysfunction (see Table 744.3). The complexity of hEDS most likely originates from the fact that it is genetically heterogeneous and represents an overlapping spectrum of disorders. Although joint hypermobility is the common denominator, symptoms may range from isolated familial joint hypermobility to the extreme multisystem disorder, which significantly impacts daily quality of life. Life expectancy is not reduced. Mild aortic root dilatation has been reported in up to 20% of affected adults. However, this mild dilatation is nonprogressive and not associated with aortic root dissection.

Vascular (vEDS) (Gene: COL3A1; Previously EDS Type IV)

vEDS is an autosomal dominant disorder that shows the most pronounced dermal thinning of all types of EDS. Consequently, the skin is translucent, and the underlying venous network is prominent, most notably over the chest region. The skin has minimal hyperextensibility but has a "velvet" texture and is often described as "doughy." The joints show increased mobility, often with instability. Congenital club foot and hip dislocation are frequently associated. Tissue fragility and arterial rupture cause significant morbidity and mortality. The majority of affected individuals experience a major vascular event before 20 years of age. Premature birth, extensive ecchymoses from trauma, a high incidence of bowel rupture (especially the colon), uterine rupture during pregnancy ($\sim 5\%$ risk), rupture of the great vessels (80% by 40 years of age), dissecting aortic aneurysm, and stroke all contribute to the increased morbidity and

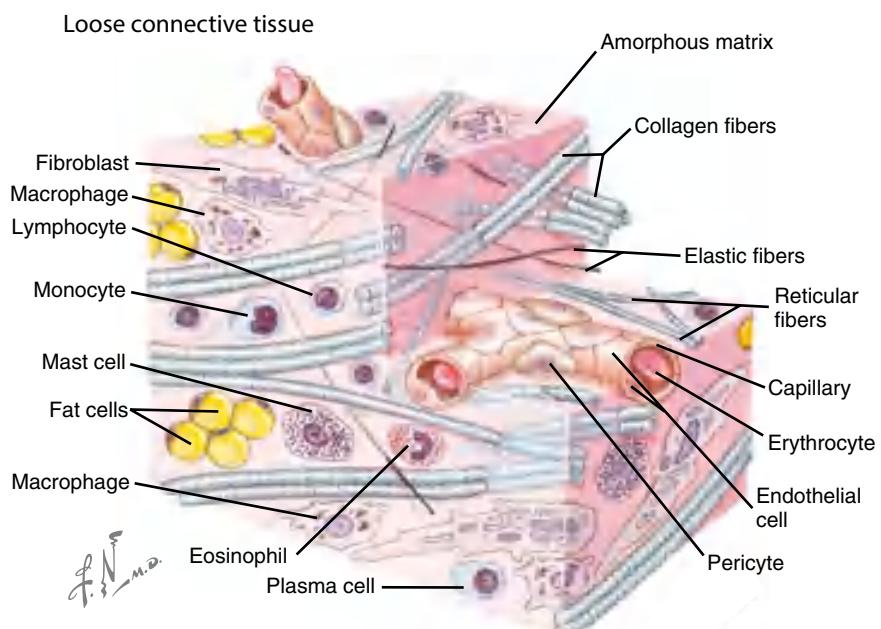


Fig. 744.1 Complex connective tissue macroenvironment illustrated by intermingled collagen and elastin fibers, nerves, mast cells, and capillaries. Both structure and function can be impacted by an abnormal connective tissue matrix. (Courtesy Netter Images, Image ID 13192. <https://netterimages.com/loose-connective-tissue-ovalle-histology-figure-31-labeled-ovalle-histology-frank-h-netter-13192.html>)



Fig. 744.2 Ehlers-Danlos syndrome (EDS). Skin hyperextensibility on the arm. (From Paller AS, Mancini AJ, eds. Hurwitz Clinical Pediatric Dermatology, 5th ed. Philadelphia: Elsevier; 2016: Fig. 6.1, p. 121.)



Fig. 744.4 Piezogenic papules on the medial aspects of the heels in a 41-yr-old patient with Ehlers-Danlos syndrome (top) and his 2-yr-old daughter (bottom). (From Poppe H, Hamm H. Piezogenic papules in Ehlers-Danlos syndrome. J Pediatr. 2013;63:1788.)



Fig. 744.3 Ehlers-Danlos syndrome (EDS). The Gorlin sign is 5 times more common in EDS than in normal individuals. Note the scars on the forehead. (From Paller AS, Mancini AJ, eds. Hurwitz Clinical Pediatric Dermatology, 5th ed. Philadelphia: Elsevier; 2016: Fig. 6.2, p. 121.)

shortened life span associated with this condition. The median age of death is estimated at 50 years. Patients are generally counseled regarding the risks associated with pregnancy and advised to avoid activities that raise intracranial or intrathoracic pressure as a result of a Valsalva maneuver (such as weight training or trumpet playing). Skin protection in childhood is important to minimize trauma (shin guards). Celiprolol, a β_1 antagonist and a β_2 agonist (vasodilator), may reduce vascular events but is not approved by the U.S. Food and Drug Administration (FDA) for use in the United States. The diagnosis is clinical and confirmed by gene sequencing of *COL3A1*.

Kyphoscoliosis (Gene: *PLOD* [Lysyl Hydroxylase Deficiency]; Previously EDS Type VI)

The kyphoscoliotic form of EDS is distinguished by the severe kyphoscoliosis that develops early in childhood. It is an autosomal recessive disorder with phenotypic overlap with the classical type of EDS in that the skin is soft and fragile, joints are hyperextensible, and easy bruising is notable from a young age. Unique

characteristics include marked hypotonia and keratoconus, with corneal fragility and globe rupture also reported. In addition, there is a higher risk for rupture of medium-sized arteries. The severity of the kyphoscoliosis may lead to restrictive lung disease with secondary pulmonary hypertension and reduced life expectancy. The diagnosis is clinical and confirmed by urine screening for an increased ratio of deoxypyridinoline to pyridinoline cross linking as well as gene sequencing of *PLOD*.



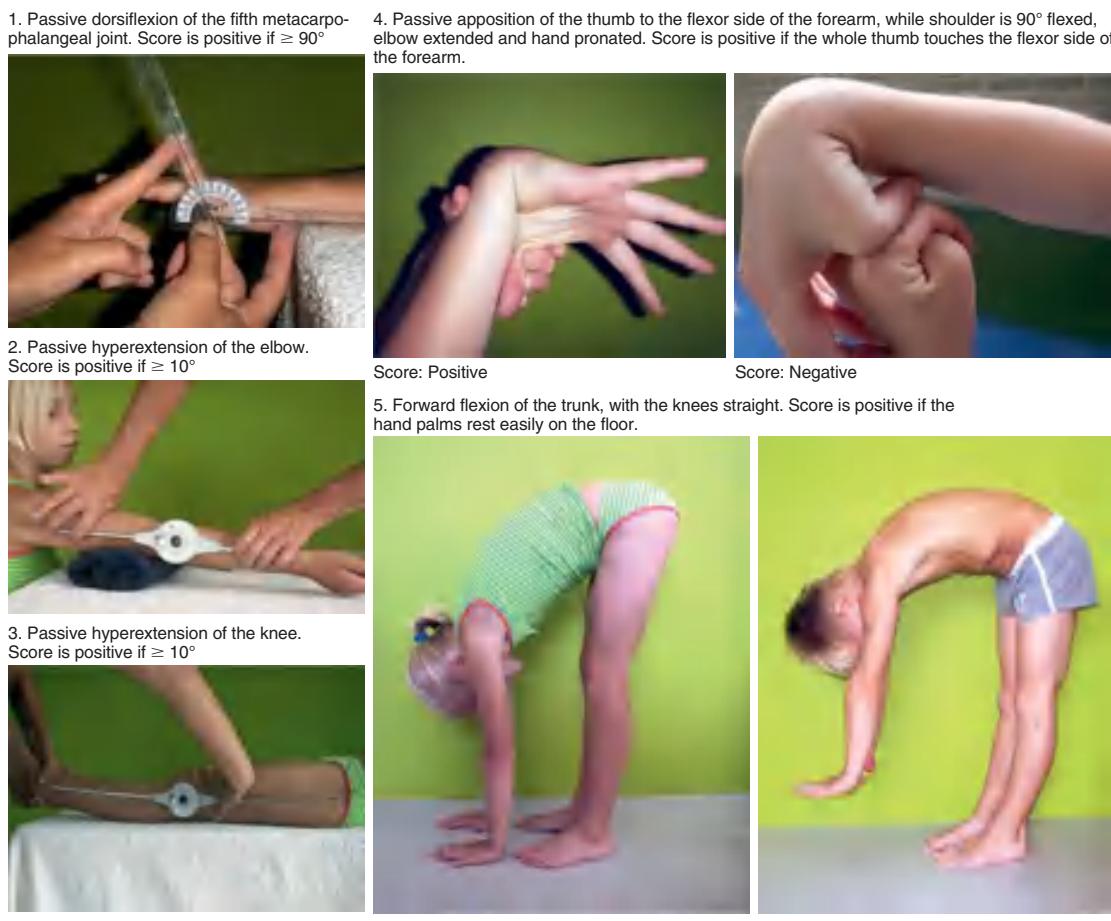
Fig. 744.5 Despite joint hyperextensibility, this patient does not meet Beighton score criteria for the extreme hypermobility seen with hypermobile Ehlers-Danlos syndrome.

Arthrochalasia (Gene: *COL1a1*, *COL1a2*; Previously EDS Types VIIA and B)

This type of EDS is inherited as an autosomal dominant disorder and characterized by severe joint instability in infancy. Joints show marked hyperextensibility with painless dislocation; the skin bruises easily and is soft and hyperextensible. Congenital hypotonia with gross motor delay is common, and kyphoscoliosis can develop in childhood. The diagnosis is clinical and confirmed by gene sequencing of *COL1A1* and *COL1A2*.

Dermatosparaxis (Type 1 Collagen N-Peptidase; Previously EDS Type VIIC)

This type of EDS is a rare autosomal recessive condition characterized by redundant skin that is soft, fragile, and bruises easily. Affected children often have a characteristic facial appearance, with skin sagging into jowls and fullness around the eyes ("puffy"). Premature rupture of membranes is common; closure of fontanelles is delayed. Additional unique features reported in this group include short limbs with brachydactyly (short fingers), frequent



*Males positive if $> 180^\circ$ for measure 2. and 3. Score: Positive

Score: Negative

Fig. 744.6 Beighton score. The range of motion of several key small and large joints is measured to provide an overview of joint hypermobility. Instability is not assessed. Scoring: 2 points for each bilateral measure in Nos. 1 to 4 and 1 point for No. 5, equaling a total possible score of 9. Hypermobility is considered significant with a score of ≥ 6 between the ages of 6 and 35. (Modified from Smits-Engelsman B, Klerks M, Kirby A. Beighton Score: a valid measure for generalized hypermobility in children. *J Pediatr* 2011;158:119–123.e4.)

Table 744.4		The Nine-Point Beighton Hypermobility Score	
THE ABILITY TO:	RIGHT	LEFT	
1. Passively dorsiflex the fifth metacarpophalangeal joint to ≥90 degrees	1	1	
2. Oppose the thenar aspect of the thumb to the volar aspect of the ipsilateral forearm	1	1	
3. Hyperextend the elbow to ≥10 degrees	1	1	
4. Hyperextend the knee to ≥10 degrees	1	1	
5. Place hands flat on the floor without bending the knees	1		
	Total: 9		

One point may be gained for each side for maneuvers 1-4, so the hypermobility score will have a maximum of 9 points if all are positive.

From Hakim A, Grahame R. Joint hypermobility. *Best Pract Res Clin Rheumatol*. 2003;17:989–1004. [Table 1](#).

Table 744.5		A Five-Part Questionnaire for Identifying Hypermobility
1. Can you now (or could you ever) place your hands flat on the floor without bending your knees?		
2. Can you now (or could you ever) bend your thumb to touch your forearm?		
3. As a child did you amuse your friends by contorting your body into strange shapes or could you do the splits?		
4. As a child or teenager did your shoulder or kneecap dislocate on more than one occasion?		
5. Do you consider yourself double-jointed?		
Answers in the affirmative to two or more questions suggest hypermobility with sensitivity 80–85% and specificity 80–90%.		

From Hakim A, Grahame R. Joint hypermobility. *Best Pract Res Clin Rheumatol*. 2003;17:989–1004. [Table 3](#).

hernias (umbilical, inguinal), blue sclerae, and bladder rupture. Joints are hypermobile. The diagnosis is confirmed by sequencing of *ADAMTS2*.

DIFFERENTIAL DIAGNOSIS

EDS represents a portion of the hereditary connective tissue disorders, many of which have unique features that enable clinical differentiation. The primary differential diagnosis would include Loeys-Dietz syndrome, which has features of both vEDS and Marfan syndrome (see Chapter 743). EDS has also been confused with MASS syndrome (mitral valve prolapse, aortic root dilation, skeletal changes, skin changes), cutis laxa (see Chapter 745), and pseudoxanthoma elasticum. In general, the skin of patients with cutis laxa hangs in redundant folds, whereas the skin of those with EDS is hyperextensible and snaps back into place when stretched. Other disorders that impact the integrity of the connective tissues—such as exposure to corticosteroids and osteogenesis imperfecta or mild myopathic disorders (Bethlem myopathy, Ullrich congenital muscular dystrophy)—can be indistinguishable in the early stages of disease (Table 744.6).

GENERAL APPROACH TO MANAGEMENT

In addition to the EDS type-specific therapies discussed under each disease, there are general approaches to help improve symptoms and avoid complications.

Table 744.6		Genetic / Mendelian Conditions Presenting with Joint Hypermobility
HEREDITARY (SOFT/NO OSSIFIED) CONNECTIVE TISSUE DISORDERS		

Ehlers-Danlos syndromes and related disorders
Fibrillinopathies (Marfan and Beals syndromes) and other disorders of the transforming growth factor-β pathway (e.g., Loey-Dietz syndrome, Shprintzen-Goldberg syndrome)
Hereditary cutis laxae

SKELETAL DYSPLASIAS
Achondroplasia and hypochondroplasia
Dysplasias with multiple dislocations (e.g., Larsen and Desboquis syndromes, *CST3*-related and *gPAPP*-related disorders)
Some spondyloepimetaphyseal dysplasias
Some *COL2A1*-related and *COL11*-related disorders
Diastrophic dysplasia
Trichorhinophalangeal dysplasia

HEREDITARY MYOPATHIES
COL6-related disorders
SEPN1-related and *RYR1*-related disorders
MYH7-related and *TTN*-related disorders
Limb girdle muscular dystrophy 2E with joint hypermobility and contractures

CHROMOSOMAL AND GENOMIC DISORDERS
Trisomy 21
47,XXY and 47,XXX
Some microdeletion and microduplication syndromes

MULTIPLE CONGENITAL ANOMALIES/INTELLECTUAL DISABILITY DISORDERS (SELECTED)

RASopathies
Kabuki syndrome
FG syndrome
Fragile X syndrome

From Castori M, Hakim A. Contemporary approach to joint hypermobility and related disorders. *Curr Opin Pediatr*. 2017;29:640–649. [Table 3](#).

Musculoskeletal pain, which initially involves the joints, eventually may become generalized and requires a combination of physical therapy and nonpharmacologic approaches (Fig. 744.7). Physical therapy should focus on enhancing the strength of the muscles supporting the affected joints. With severe recurrent sprains or dislocations, bracing may be necessary. Pain medication for low- to moderate-intensity pain could include nonsteroidal antiinflammatory drugs (however, their platelet-inhibiting action may increase the risk of cutaneous bleeding). Higher-intensity pain may require other agents, such as selective serotonin receptor inhibitors or low-dose tricyclic antidepressants. Muscle relaxants or antiepileptic agents should be avoided because they may increase fatigue. Surgery for joint dislocations should be avoided if possible as should prolonged periods of inactivity (which result in rapid muscle deconditioning) (Table 744.7). If surgery is needed for any complication, the sutures should approximate the margins, suture tension should be avoided, and the sutures should be retained longer than usual. Other approaches to pain include cognitive behavioral therapy, acupuncture, and transcutaneous electrical nerve stimulation (TENS).

Chronic fatigue should be approached by supporting good sleep hygiene and avoiding sedating medications (see Table 744.7). Patients at risk for arterial bowel or uterine rupture should be counseled about preventive measures, appropriate medications (see specific subtype), and early warning signs of organ rupture.

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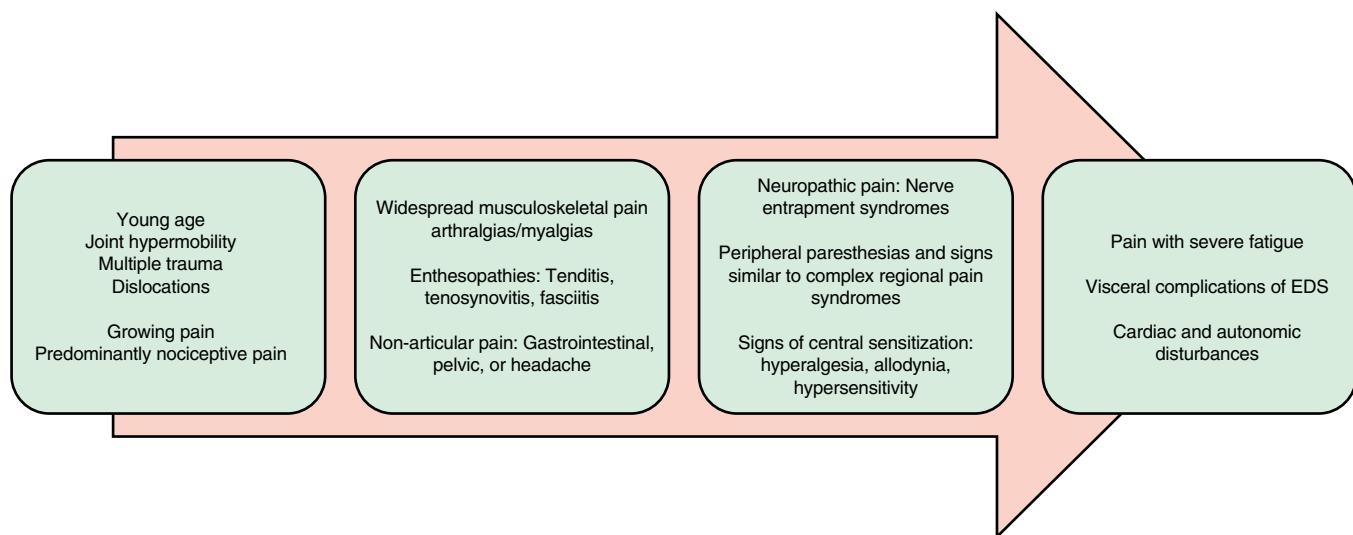


Fig. 744.7 Characteristics of pain in Ehlers-Danlos syndrome that progress in clinical stages. (From Zhou Z, Rewari A, Shanthanna H. Management of chronic pain in Ehlers-Danlos syndrome. *Medicine*. 2018;97:e13115.)

Table 744.7 Lifestyle Recommendations for Hypermobile Ehlers-Danlos Syndrome

- Promote regular aerobic fitness
- Promote fitness support with strengthening, gentle stretching, and proprioception exercise
- Promote postural and ergonomic hygiene, especially during sleep, at school, and in the workplace
- Promote weight control (body mass index [BMI] <25)
- Promote daily relaxation activities
- Promote lubrication during sexual intercourse
- Promote early treatment of malocclusion
- Avoid high-impact sports/activities
- Avoid low environmental temperatures
- Avoid prolonged sitting positions and prolonged recumbency
- Avoid sudden head-up postural change
- Avoid excessive weightlifting/carrying
- Avoid large meals (especially of refined carbohydrates)
- Avoid hard foods intake and excessive jaw movements (e.g., ice, gums)
- Avoid bladder irritant foods (e.g., coffee and citrus products)
- Avoid nicotine and alcohol intake

Note: these recommendations are intended as flexible indications for ameliorating quality of life and do not represent lifesaving solutions.

Adapted from Castori M, Morlino S, Celletti C, et al. Management of pain and fatigue in the joint hypermobility syndrome (aka Ehlers-Danlos syndrome, hypermobility type): principles and proposal for a multidisciplinary approach. *Am J Med Genet*. 2012;158:2055–2070.



Fig. 745.1 Pendulous folds of skin of an infant with cutis laxa.

X-linked or acquired forms (Fig. 745.2, Tables 745.1 and 745.2). Acquired CL may develop after a febrile illness, inflammatory skin diseases such as lupus erythematosus or erythema multiforme, amyloidosis, urticaria, angioedema, hypersensitivity reactions to penicillin, or in neonates born to women who were taking penicillamine.

CLINICAL MANIFESTATIONS

CL may demonstrate widespread folds of **loose skin**, or changes may be mild and limited in extent, resembling anetoderma. Patients with severe cutis laxa have characteristic facial features; they present with an aged appearance with sagging jowls (“bloodhound” appearance; see Fig. 745.1), a hooked nose with everted nostrils, a short columella, a long upper lip, and everted lower eyelids. The skin is also lax elsewhere on the body and has been described as resembling an ill-fitting suit. Hyperelasticity and hypermobility of the joints as seen in the Ehlers-Danlos syndromes are not present. Many infants have a hoarse cry, probably as a result of laxity of the vocal cords. Tensile strength of the skin is normal. Other features are noted in Table 745.3.

The **autosomal dominant** form of CL (ADCL) is typically caused by pathogenic variants in *ELN*, which encodes elastin, an essential extracellular matrix protein responsible for maintenance of skin elasticity. ADCL has predominant skin involvement but can have risk for aortic aneurysm and emphysema. It typically manifests in infancy; it may be associated with intrauterine growth restriction, ligamentous laxity, and delayed closure of the fontanelles.

Chapter 745

Cutis Laxa

Leah Lalor

Cutis laxa syndromes encompass a group of rare multisystem disorders that include loose redundant skinfolds as hallmark clinical feature (Fig. 745.1). Cutis laxa results from impaired elastic fiber assembly and homeostasis, and the known underlying gene defects affect different extracellular matrix proteins, intracellular trafficking, or cellular metabolism.

Cutis laxa (CL) may present in **autosomal recessive** (ARCL1A, ARCL1B, ARCL1C, ARCL2A, ARCL2B), **autosomal dominant** (ADCL),

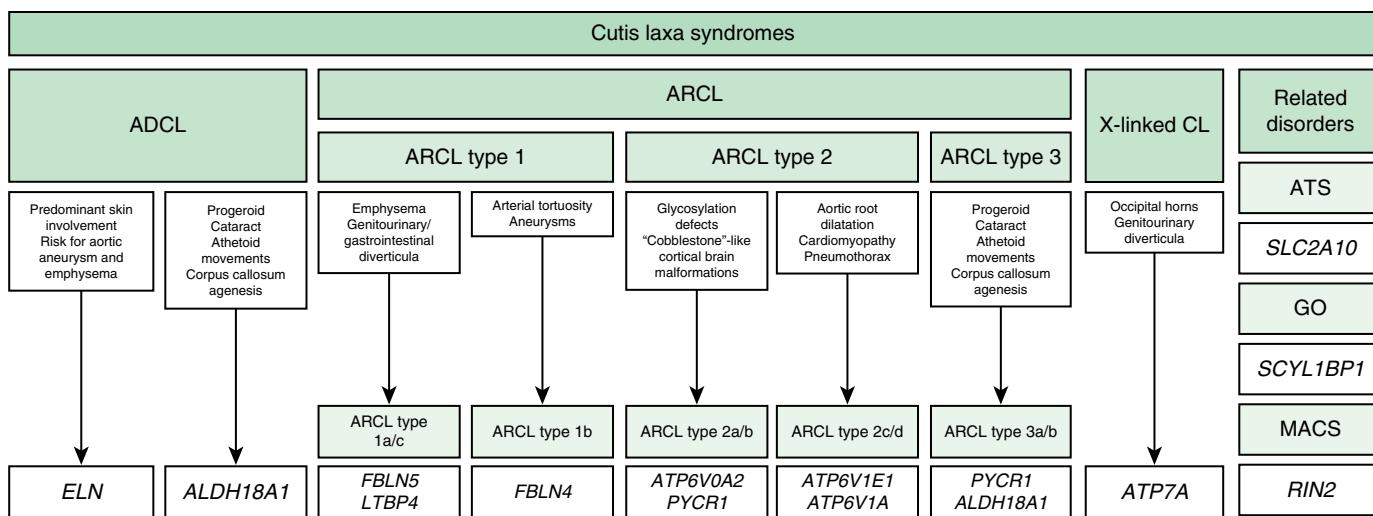


Fig. 745.2 The spectrum of cutis laxa disorders. ADCL, Autosomal dominant cutis laxa; ARCL, autosomal recessive cutis laxa; ATS, arterial tortuosity syndrome; GO, geroderma osteodysplasticum; MACS, macrocephaly-alopecia-cutis laxa-scoliosis. (From Beyens A, Boel A, Symoens S, et al. Cutis laxa: a comprehensive overview of clinical characteristics and pathophysiology. *Clin Genet.* 2021;99:53–66. Fig.1.)

Table 745.1 Disorders to Consider in the Differential Diagnosis of Cutis Laxa

DISEASE NAME	GENE SYMBOL	MIM #	INHERITANCE	CLINICAL FINDINGS			DEVELOPMENTAL DELAY
				CUTIS LAXA	EMPHYSEMA	ANEURYSMS	
ALDH18A1-related cutis laxa	ALDH18A1	612652	AR	+	-	-	++
FBLN5-related cutis laxa	FBLN5	219100	AR	+++	+++	-	-
EFEMP2-related cutis laxa	EFEMP2(FBLN4)	219100	AR	++	++	+++	-
Autosomal recessive cutis laxa type 2A	ATP6V0A2 219200	278250 219200	AR	++	-	-	++
Autosomal dominant cutis laxa	ELN or FBLN5	123700	AD	+	+	+	-
Geroderma osteodysplastica	GORAB	231070	AR	++	-	-	-
De Barsy syndrome (PYCR1-related progeroid syndrome)	PYCR1	219150	AR	+	-	-	+++
Autosomal recessive cutis laxa type 2B	PYCR1	612940	AR	+	-	-	+++
LTBP4-related cutis laxa	LTBP4	613177	AR	+	++	+	+
RIN2-related cutis laxa	RIN2	613075	AR	+	-	-	±

Reproduced with permission from Van Maldergem L, Dobyns W, Kornak U. ATP6V0A2-Related Cutis Laxa. 2009 Mar 19 [Updated 2011 May 10]. In: Pagon RA, Bird TD, Dolan CR, et al., eds. GeneReviews[Internet]. Seattle (WA): University of Washington, Seattle; 1993. Available from <http://www.ncbi.nlm.nih.gov/books/NBK5200/>

Pathogenic variants in *ALDH18A1*, which encodes delta-1-pyrroline-5-carboxylate synthetase (P5CS), a key enzyme in the synthesis of proline (an abundant amino acid in elastin), can cause autosomal dominant or recessive CL. Notably, pathogenic variants in *PYCR1*, which encodes pyrroline-carboxylate reductase 1, another enzyme in this pathway, cause recessive CL (ARCL3). Each of these proline synthesis-related CL subtypes can also present with

progeroid features, cataracts, athetoid movements, and corpus callosum anomalies.

Autosomal recessive CL is divided into three general subtypes: type 1 (ARCL1), with cardiopulmonary complications, type 2 (ARCL2), with CNS and skeletal anomalies, and type 3 (ARCL3; de Barsy syndrome), which adds ocular findings to the type 2 features. Overall, these individuals can present with multiple hernias, rectal prolapse, diaphragmatic

Table 745.2 Associations with Acquired Cutis Laxa

Infections
<i>Toxocara canis</i> (cat-scratch)
<i>Treponema pallidum</i> (syphilis)
<i>Borrelia burgdorferi</i> (Lyme disease)
<i>Onchocerca volvulus</i> (onchocerciasis)
Medications
Isoniazid
Penicillins
D-penicillamine
Inflammatory diseases
Celiac disease
Sarcoidosis
Dermatitis herpetiformis
Sweet syndrome
Rheumatic disorders
Systemic lupus erythematosus
Rheumatoid arthritis
Others
α_1 -antitrypsin deficiency
Mastocytosis
Nephrotic syndrome
Amyloidosis
Malignancy

From Paller AS, Mancini AJ. *Hurwitz Clinical Pediatric Dermatology*, 6th ed. Philadelphia: Elsevier, 2022; Box 6.6, p. 151.

Table 745.3 Most Common Other Features of Cutis Laxa

- Facial dysmorphism
- Aortic dilatation
- Pulmonary artery stenosis
- Pulmonary emphysema
- Diverticulae: gastrointestinal, genitourinary
- Uterine or rectal prolapse
- Ventral, hiatal, inguinal hernias

Modified from Paller AS, Mancini AJ. *Hurwitz Clinical Pediatric Dermatology*, 6th ed. Philadelphia: Elsevier, 2022; Box 6.4, p. 148.

atony, diverticula of the gastrointestinal and genitourinary tracts, cor pulmonale, emphysema, pneumothoraces, peripheral pulmonary artery stenosis, and aortic dilation. Characteristic facial features include downward-slanting palpebral fissures, a broad, flat nose, and large ears. Skeletal anomalies, dental caries, growth retardation, and developmental delay also occur. Such patients often have a shortened life span.

ARCL1 is comprised of three subtypes. Subtypes ARCL1a and ARCL1c (Urban-Rifkin-Davis syndrome), caused by dominant pathogenic variants in *FBLN5* and *LTPB4*, respectively, are similar disorders and, in addition to skin findings, more frequently develop emphysematous lung changes and mechanical insufficiency of the gastrointestinal and genitourinary tract wall. Subtype ARCL1b, caused by pathogenic variants in *FBLN4*, in addition to skin findings, typically develops elongation, tortuosity, and aneurysms of the large- and middle-sized arteries.

ARCL2 often presents with delays in neuromotor development and can include epilepsy and cortical or cerebellar malformations. Recessive pathogenic variants in *ATP6V0A2* (ARCL 2a) are more common and include N- or O-glycosylation defects and pathogenic variants *PYCR1* (ARCL2b).

ARCL2 with recessive pathogenic variants in *ATP6V1E1* (ARCL2c) and *ATP6V1A* (ARCL2d), genes encoding key enzymes in acidification of intracellular organelles, can include N- or O-glycosylation defects and demonstrate increased frequency of aortic root dilatation, cardiomyopathy, and pneumothorax.

X-linked CL, also referred to as **occipital horn syndrome**, is caused by pathogenic variants of *ATP7A* that encodes a Cu²⁺-transporting adenosine triphosphatase, α -polypeptide. This clinical presentation is allelic with Menkes disease (see Chapter 639.5) but is at the milder end of that spectrum.

Cutis laxa-like skin changes may also be seen in association with multiple other syndromes, including Lenz-Majewski syndrome, hyperostotic dwarfism, SCARF (skeletal abnormalities, cutis laxa, craniostenosis, ambiguous genitalia, retardation, facial abnormalities) syndrome, wrinkling skin syndrome, arterial tortuosity syndrome (ATS), gerodermia osteodysplasia, macrocephaly alopecia cutis laxa scoliosis syndrome (MACS), and Costello syndrome.

HISTOLOGY

Histologically, elastic tissue is reduced throughout the dermis, with fragmentation, distention, and clumping of the elastic fibers. This often results in bare microfibrils of random directionality. The light microscopic appearance of elastic fibers in CL patients is typically not able to discern between different subtypes as they appear reduced and fragmented in all.

TREATMENT

Treatment of the skin findings in cutis laxa is largely supportive, although textural improvement and symptomatic relief using resurfacing lasers for acquired CL has been reported.

Regarding medical management, as a general rule, unrelated to the underlying subtype, elastic fiber defects warrant regular assessment of pulmonary, cardiovascular, and urinary systems. Yearly echocardiography is recommended in dominant CL, ARCL1a/c, and ARCL2c. More intensive echocardiographic follow-up is needed in ARCL1b and ATS (every 3 months in ARCL1b; every 3 months until the age of 5 in ATS), while in the remaining subtypes an examination every 3–5 years is sufficient. In ARCL1, MRI head-to-pelvis should be repeated yearly (ARCL1b) or every 3–5 years (ARCL1a/c and ATS).

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Section 5

Metabolic Bone Disease

Chapter 746

Bone Structure, Growth, and Hormonal Regulation

Rebecca J. Gordon and
Catherine M. Gordon

See also Chapters 69 and 610.

Bone is a rigid organ but metabolically active in that it is constantly being formed (**modeled**) and reformed (**remodeled**). It is capable of rapid turnover, bearing weight, and withstanding the stresses of various physical activities. Bone is the major body reservoir for calcium, phosphorus, and magnesium. Other functions of bone include organ protection, structure, movement, and sound transmission. It is also an endocrine organ that produces fibroblast growth factor 23 (FGF23), which regulates renal phosphate handling. Disorders that affect this organ and the process of mineralization are designated **metabolic bone diseases**.

The human skeleton consists of a protein matrix, largely composed of a collagen-containing protein, osteoid, on which is deposited a crystalline mineral phase. Collagen-containing osteoid accounts for 90% of bone protein; other proteins, including osteocalcin, which

contains γ -carboxyglutamic acid, are also present. Synthesis of osteocalcin depends on vitamin K and vitamin D; in states with high bone turnover, serum osteocalcin values are often elevated. Osteocalcin appears to enhance insulin secretion and sensitivity and reduce fat stores.

The microfibrillar matrix of osteoid permits deposition of highly organized calcium phosphate crystals, including hydroxyapatite [$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$] and octacalcium phosphate [$\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$], plus less-organized amorphous calcium phosphate, calcium carbonate, sodium, magnesium, and citrate. Hydroxyapatite is deep within bone matrix, whereas amorphous calcium phosphate coats the surface of newly formed or remodeled bone.

Because bone growth and turnover rates are high during childhood, many clinical and osseous features of metabolic bone diseases are more prominent in children than in adults. The growth pattern of bones is an acceleration of bone growth (length) of the limbs during prepubescence, increased growth (length) of the trunk (spine) during early adolescence, and increased bone mineral deposition in late adolescence.

The use of dual-energy x-ray absorptiometry (DXA) or quantitative CT permits measurement of both mineral content and bone density in healthy subjects and children with metabolic bone disease. DXA exposes the patient to less radiation than a chest radiograph and significantly less than quantitative CT and is therefore most commonly used in clinical practice (see Chapter 749). **Bone growth** occurs in children by the process of calcification of the cartilage cells present at the ends of bone. In accord with the prevailing extracellular fluid calcium and phosphate concentrations, mineral is deposited in chondrocytes or cartilage cells set to undergo mineralization. The main function of the vitamin D–parathyroid hormone (PTH)–FGF23–endocrine axis is to maintain the extracellular fluid calcium and phosphate concentrations at appropriate levels to permit mineralization.

Other hormones also appear to regulate the growth and mineralization of cartilage, including growth hormone acting through insulin-like growth factors, thyroid hormones, insulin, leptin, ghrelin, and androgens and estrogens during the pubertal growth spurt. Supraphysiologic concentrations of glucocorticoids impair cartilage function and bone growth and augment bone resorption.

Rates of bone formation are coordinated with alterations in mineral metabolism in both the intestine and kidneys, where a number of hormones regulate the processes. Inadequate dietary intake or intestinal absorption of calcium causes a fall in serum levels of calcium and its ionized fraction. This decrease serves as the signal for PTH synthesis and secretion, resulting in greater bone resorption (which raises the serum calcium level) and enhanced distal tubular reabsorption of calcium. It also promotes higher rates of renal synthesis of 1,25-dihydroxyvitamin D [$1,25(\text{OH})_2\text{D}$] or calcitriol, the most active metabolite of vitamin D (Fig. 746.1). **Calcium homeostasis** is thus controlled by the intestine because the availability of $1,25(\text{OH})_2\text{D}$ ultimately determines the fraction of ingested calcium that is absorbed.

Phosphate homeostasis is regulated by the kidneys because intestinal phosphate absorption is nearly complete, and renal excretion determines the serum level of phosphate. Excessive intestinal phosphate absorption causes a fall in serum levels of ionized calcium and a rise in PTH secretion, resulting in phosphaturia, thus lowering the serum phosphate level and permitting the calcium level to rise. Hypophosphatemia blocks PTH secretion and promotes renal $1,25(\text{OH})_2\text{D}$ synthesis. This latter compound also promotes greater intestinal phosphate absorption. The important role of FGF23 in phosphate homeostasis is described later.

Vitamin D can be synthesized in the skin under the influence of ultraviolet (UV) irradiation, or it can be absorbed from the diet. It is converted to $25(\text{OH})\text{D}3$ (vitamin D3) in the liver and then further converted by the kidney. The skin contains 7-dehydrocholesterol, which is converted to vitamin D3 [$25(\text{OH})\text{D}3$] by UV radiation; other inactive vitamin D sterols are also produced (see Chapter 69). Vitamin D3 is then transported in the bloodstream to the liver by a vitamin D-binding protein (DBP); DBP binds all forms of vitamin D. The plasma concentration of free or nonbound vitamin D is much lower than the level of DBP-bound vitamin D metabolites.

Vitamin D also can enter the metabolic pathway by ingestion of dietary vitamin D2 (ergocalciferol) or vitamin D3 (cholecalciferol), the latter of which is more potent, and both of which are absorbed from the intestine because of the action of bile salts. After absorption, ingested vitamin D is

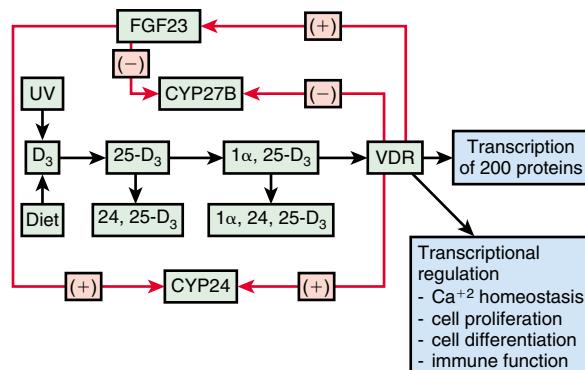


Fig. 746.1 Vitamin D metabolism. Vitamin D can be synthesized in the skin under the influence of ultraviolet (UV) irradiation, or it can be absorbed from the diet. It is converted to $25(\text{OH})\text{D}3$ (vitamin D3) in the liver and then further converted by the kidney. The enzyme cytochrome P450 (CYP) 27B converts $25(\text{OH})\text{D}3$ to $1\alpha,25-(\text{OH})_2\text{D}3$. $1,25(\text{OH})_2\text{D}3$ binds to vitamin D receptor (VDR), which, after transport to the nucleus, acts to induce the transcription of more than 200 proteins. The functions of some of the proteins are indicated. VDR activation leads to productions of fibroblast growth factor 23 (FGF23). FGF23 induces phosphaturia (not shown), upregulates CYP 24, and downregulates CYP 27B.

transported by chylomicrons to the liver, where, along with skin-derived vitamin D3, it is converted to 25-hydroxyvitamin D [25(OH)D]. The 25(OH)D is next transported by DBP to the kidneys, where it undergoes further metabolism. 25(OH)D is the main circulating vitamin D metabolite in humans (Table 746.1). Because the synthesis of 25(OH)D is weakly regulated by feedback, its plasma level rises in summer and decreases during winter. High vitamin D intake raises the plasma level of 25(OH)D to many times above normal, but the parent vitamin D compound itself is absorbed by adipose tissue.

In the kidneys, 25(OH)D undergoes further hydroxylation, depending on the prevailing serum concentration of calcium, phosphate, PTH, and FGF23. If the calcium or phosphate level is reduced or the PTH level is elevated, the enzyme 25(OH)D-1-hydroxylase is activated and $1,25(\text{OH})_2\text{D}$ is formed. $1,25(\text{OH})_2\text{D}_3$ binds to a vitamin D receptor, which after transport to the nucleus, acts to induce the transcription of 200-400 proteins and peptides. The functions of some of the proteins are known.

Another class of proteins important in the regulation of mineral balance and vitamin D synthesis are the **phosphatonins**. Among these are FGF23, sFRP-4 (secreted Frizzled-related protein 4), and MEPE (matrix extracellular phosphoglycoprotein). Overexpression of FGF23 results in hypophosphatemia, phosphaturia, reduced serum $1,25(\text{OH})_2\text{D}$ values, and some forms of rickets. Disorders of phosphate balance, including hyper- and hypophosphatemia, can relate to loss or gain of function of these phosphatonins (see Fig. 746.1).

Vitamin D receptor activation by $1,25(\text{OH})_2\text{D}$ leads to production of FGF23. FGF23 is produced by osteocytes and targets another organ, the kidney, to promote phosphaturia. FGF23 reduces expression/embedding of two sodium phosphate transporters into the renal proximal tubule, resulting in higher levels of urinary phosphate excretion. This bone-derived hormone also inhibits renal hydroxylase activity (CYP 27B1) and promotes 24-hydroxylase activity, with resultant decrease in $1,25(\text{OH})_2\text{D}$ levels.

The active metabolite, $1,25(\text{OH})_2\text{D}$, circulates at a level that is only 0.1% of the level of 25(OH)D (see Table 746.1) and acts on the intestine to increase the active transport of calcium and stimulate phosphate absorption. Because 1 α -hydroxylase is a mitochondrial enzyme that is tightly feedback regulated, the synthesis of $1,25(\text{OH})_2\text{D}$ declines after serum calcium or phosphate values return to normal. Excessive $1,25(\text{OH})_2\text{D}$ is converted to an inactive metabolite. In the presence of normal or elevated serum calcium or phosphate concentrations, the renal 25(OH)D-24-hydroxylase is activated, producing 24,25-dihydroxyvitamin D [$24,25(\text{OH})_2\text{D}$], which is a pathway for the removal of excess vitamin D; serum levels of $24,25(\text{OH})_2\text{D}$ (1-5 ng/mL) increase after ingestion of large amounts of vitamin D (see Fig. 746.1) or in the presence of increased concentrations of FGF23. Although hypervitaminosis D and production of

Table 746.1 Vitamin D Metabolic Values in Plasma of Normal Healthy Subjects

METABOLITE	PLASMA VALUE
Vitamin D2	1-2 ng/mL
Vitamin D3	1-2 ng/mL
25(OH)D2	4-10 ng/mL
25(OH)D3	26-70 ng/mL
TOTAL 25(OH)D	20-80 ng/mL*
24,25(OH)2D	1-4 ng/mL
1,25(OH)2D	
Infancy	70-100 pg/mL
Childhood	30-50 pg/mL
Adolescence	40-80 pg/mL
Adulthood	20-35 pg/mL

*The Institute of Medicine states that a value of 25(OH)D of 20 ng/mL is the lower limit of normal for the general population. In contrast, the Endocrine Society defines vitamin D deficiency as having a serum level of less than 20 ng/mL, and insufficiency as a serum level between 21-29 ng/mL.

inactive metabolites can occur after oral dosing, extensive skin exposure to sunlight does not usually produce toxic levels of 25(OH)D3, suggesting natural regulation of the production of this metabolite in cutaneous tissue.

Serum 1,25(OH)₂D levels are higher in children than in adults, are not as subject to seasonal variability, and peak during the first year of life and again during the adolescent growth spurt. These values must be interpreted in light of the prevailing serum calcium, phosphate, and PTH values, and with regard to the entire vitamin D metabolite profile.

Mineral deficiency prevents the normal process of bone mineral deposition. If mineral deficiency occurs at the growth plate, growth slows and bone age is retarded, a condition called **rickets**. Poor mineralization of trabecular bone resulting in a greater proportion of unmineralized osteoid is the condition of osteomalacia. Rickets is found only in growing children before fusion of the epiphyses, whereas osteomalacia is present at all ages. All patients with rickets have osteomalacia, but not all patients with osteomalacia have rickets. These conditions should not be confused with osteoporosis, a condition of equal loss of bone volume and mineral (see [Chapter 749](#)).

Rickets may be classified as calcium-deficient or phosphate-deficient rickets. Because both calcium and phosphate ions constitute bone mineral, the insufficiency of either type in the extracellular fluid that bathes the mineralizing surface of bone results in rickets and osteomalacia. The two types of rickets are distinguishable by their clinical manifestations ([Table 746.2](#)). Rickets can also occur in the face of mineral

Table 746.2 Clinical Variants of Rickets and Related Conditions

TYPE	SERUM CALCIUM LEVEL	SERUM PHOSPHORUS LEVEL	ALKALINE PHOSPHATASE ACTIVITY	URINE CONCENTRATION OF AMINO ACIDS	GENETICS	GENE DEFECT KNOWN
CALCIUM DEFICIENCY WITH SECONDARY HYPERPARATHYROIDISM*						
<i>Lack of Vitamin D</i>						
Lack of exposure to sunlight	N or L	L	E	E		
Dietary deficiency of vitamin D	N or L	L	E	E		
Congenital	N or L	L	E	E		
<i>Other Deficiencies</i>						
Malabsorption of vitamin D	N or L	L	E	E		
Liver diseases	N or L	L	E	E		
Anticonvulsant drug	N or L	L	E	E		
Renal osteodystrophy	N or L	E	E	V		
Vitamin D-dependent type I	L	N or L	E	E	AR	Y
PRIMARY PHOSPHATE DEFICIENCY (NO SECONDARY HYPERPARATHYROIDISM)						
Genetic primary hypophosphatemia	N	L	E	N	XL, AD, AR	Y
X-linked hypophosphatemic rickets					XL	Y
Autosomal dominant hypophosphatemic rickets					AD	Y
Autosomal recessive hypophosphatemic rickets					AR	Y
<i>Fanconi Syndrome</i>						
Cystinosis	N	L	E	E	AR	Y
Tyrosinosis	N	L	E	E	AR	Y
Lowe syndrome	N	L	E	E	XL	Y
Acquired	N	L	E	E		
<i>Phosphate Deficiency or Malabsorption</i>						
Parenteral hyperalimentation	N	L	E	N		
Low phosphate intake	N	L	E	N		

Continued

Table 746.2 Clinical Variants of Rickets and Related Conditions—cont'd

Type	Serum Calcium Level	Serum Phosphorus Level	Alkaline Phosphatase Activity	Urine Concentration of Amino Acids	Genetics	Gene Defect Known
<i>Other</i>						
Renal tubular acidosis, type II proximal	N	L	E	N		Y
Tumor-induced osteomalacia	N	L	E	N		Y
END-ORGAN RESISTANCE TO 1,25(OH)₂D₃						
Vitamin D-dependent type II (several variants)	L	L or N	E	E	AR	Y
RELATED CONDITIONS RESEMBLING RICKETS						
Hypophosphatasia	N	N	L	Phosphoethanolamine elevated	AR	Y
Metaphyseal Dysostosis						
Jansen type	E	N	E	N	AD	Y
Schmid type	N	N	E	N	AD	Y

*Deficiency of vitamin D; low 25(OH)D and no stimulation of higher 1,25(OH)₂D values.

AD, Autosomal dominant; AR, autosomal recessive; E, elevated; L, low; N, normal; V, variable; XL, X-linked; Y, yes.

deficiency, despite adequate vitamin D stores. True dietary calcium deficiency rickets are found in some parts of Africa but rarely in North America or Europe. A form of phosphate-deficiency rickets can occur in infants, given prolonged administration of phosphate-sequestering aluminum salts as a treatment for colic or gastroesophageal reflux. This results in the phosphate depletion syndrome.

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Chapter 747

Hypophosphatasia

Nourah N. Almutlaq and Linda A. DiMeglio

Hypophosphatasia (HPP) is a rare inborn error of metabolism in which tissue-nonspecific (liver, bone, kidney) alkaline phosphatase isoenzyme (TNSALP) activity is deficient, although activity of the intestinal and placental isoenzymes is normal. Decreased serum alkaline phosphatase (ALP) concentrations are the hallmark of HPP.

Pathogenic variants in the *ALPL* gene reduce the TNSALP enzyme activity to below the level essential for normal bone and teeth mineralization. More than 340 variants have been identified to date. Missense variants are the most common; however, splice-site, small deletions, and frameshift variants also have been found. The high heterogeneity of the disease is related to the inheritance pattern and different missense variants' varied TNSALP activity effects. Although the genotype/phenotype correlation is not very consistent, the more severe forms are recessively inherited and milder disease is dominantly inherited.

The clinical spectrum of HPP ranges from a very severe, typically lethal, perinatal form to a mild form with late-adult onset presenting with nonpathognomonic symptoms such as arthropathy and musculoskeletal pain. A nosology describing seven forms of the condition, ranging from neonatal lethal disease to odonto-hypophosphatasia, which only affects teeth with no skeletal deformities, is employed. (Subtypes and features of HPP are shown in Table 747.1.) The most common signs across subtypes are bone

demineralization and premature loss of teeth with intact roots in the setting of low ALP.

The most severe **perinatal HPP** cases are lethal in utero or shortly after birth in untreated newborns. Infants have profound skeletal hypomineralization with short bones that lead to chest deformities and subsequent hypoplastic lungs. Infants may also have anemia with intracranial hemorrhage, periodic apnea, and pyridoxine-dependent seizures (Fig. 747.1A). **Infantile HPP** is next on the continuum. These infants present before 6 months of age with overlapping symptoms to perinatal HPP, including respiratory distress from severe lung hypoplasia. They can also have irritability and failure to thrive explained by the hypercalcemia/hypercalcuria (leading to nephrocalcinosis) and premature craniostenosis (can lead to increased intracranial pressure). X-rays reveal irregular ossification, punched-out areas, and metaphyseal cupping. Before the availability of enzyme replacement therapy with asfotase alfa, mortality was estimated at 50% and survivors had significant disability. This subset of patients can also improve spontaneously as affected children mature, although early death from renal failure or flail chest leading to pneumonia can occur.

Of note, a **benign prenatal** form of hypophosphatasia also exists. It is seen in newborns with low ALP and skeletal abnormalities in utero or at birth that improve spontaneously over time.

The next category of hypophosphatasia manifests in childhood (after 6 months of life) or late adolescence (**hypophosphatasia tarda**) (see Fig. 747.1B). These children present with premature exfoliation of primary teeth (with the root intact because of poorly mineralized dental cementum), mild skeletal deformities, fracture, and variable short stature. Some children have symptoms of skeletal pain and muscle weakness. Long bones can have characteristic "tongues" of radiolucency (Fig. 747.2).

An **adult hypophosphatasia** form manifests in middle age (although some patients recount a history of early deciduous tooth loss or rickets). It is characterized by nonspecific symptoms and a milder course than pediatric forms. This form may be diagnosed after affected individuals present with osteopenia/osteoporosis, recurrent metaphyseal stress fractures (particularly of the metatarsals and tibiae), and femoral pseudofractures. Affected individuals can also have psychiatric symptoms (depression/anxiety) chondrocalcinosis, osteoarthritis, myopathy, nephrocalcinosis, and permanent tooth loss between 40–60 years of age.

Rarely, patients presenting with identical clinical and radiographic patterns have normal serum alkaline phosphatase activity but increased concentrations of phosphoethanolamine, inorganic phosphate, and pyridoxal-5-phosphate. Their disease has been labeled **pseudohypophosphatasia** and might represent the presence of a variant alkaline

Table 747.1 Hypophosphatasia Main Subtypes and Features

SUBTYPE	ONSET	INHERITANCE	CLINICAL FEATURES
Perinatal severe	Perinatal	Recessive	<ul style="list-style-type: none"> Lethal in all cases without enzyme replacement Prenatal US: absent skeletal mineralization, bowed/short long bones, fractures, osteochondral spurs, and pretibial dimpling Death from respiratory distress from chest deformities and lung hypoplasia Vitamin B6-dependent seizures
Prenatal benign	Perinatal	Dominant and recessive	<ul style="list-style-type: none"> Skeletal deformity in utero without fractures ("bent not broken") Improves spontaneously, benign course
Infantile	≤ 6 mo	Recessive	<ul style="list-style-type: none"> Lethal in approximately 50% of cases without enzyme replacement Appear normal at birth Severe bone demineralization leads to rachitic chest deformities and resultant pulmonary hypoplasia Hypercalcemic hypercalciuria (leads to nephrocalcinosis) Craniosynostosis
Childhood	6 mo-18 yr	Dominant and recessive	<ul style="list-style-type: none"> Premature loss of deciduous teeth with root intact in children <5 yr Rickets/fractures/skeletal deformities "Tongues" of radiolucency on x-ray Chronic joint/bone pain Short stature
Adult	Adulthood	Dominant and recessive	<ul style="list-style-type: none"> Mild Osteoporosis Stress fractures, osteomalacia, and chondrocalcinosis
Odontohypophosphatasia	Childhood	Dominant and recessive	<ul style="list-style-type: none"> Mildest form of HPP No skeletal deformities; premature exfoliation of primary and/or permanent teeth Severe dental caries

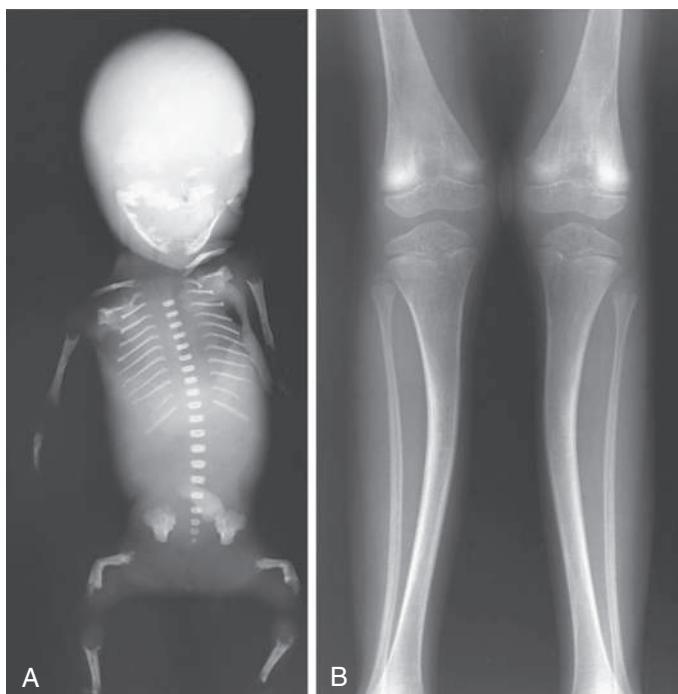


Fig. 747.1 A, Fetus with congenital lethal hypophosphatasia showing thin wavy ribs, platyspondyly, missing cervical vertebrae, ossification, and bent femurs. B, A 7-yr-old with hypophosphatasia tarda showing osteopenia, bent tibias, and punched-out metaphyseal lesions.

phosphatase isoenzyme that catalyzes artificial substrates in an alkaline environment (e.g., a test tube), but not *in vivo* with natural substrates.

Because of the heterogeneous clinical manifestations of HPP, which often mimics other skeletal disorders, delays and misdiagnosis are common. Clinical features and radiologic findings in the setting of low ALP for age or other biomarkers of the disorder should raise suspicion. Initially the diagnosis might be suspected in the presence of a low serum ALP (adjusted for age and natal sex) and supported with an increased urinary phosphoethanolamine PEA level or high vitamin B6 concentrations. However, other etiologies for low ALP should be ruled out (Fig. 747.3 and Table 747.2).

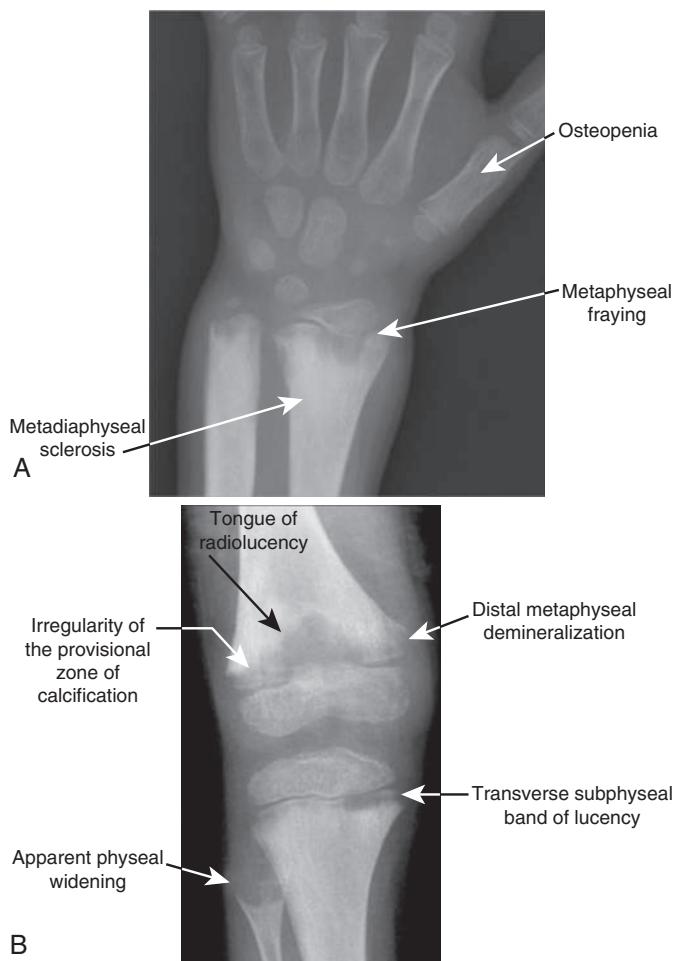


Fig. 747.2 Skeletal features of untreated hypophosphatasia. Untreated, the radiographic features of hypophosphatasia of the wrist (A) and knee (B) in children include osteopenia, metaphyseal fraying, metaphyseal flaring, metadiaphyseal sclerosis, characteristic "tongues" of radiolucency, irregularity of the provisional zone of calcification, distal metaphyseal demineralization, transverse subphyseal band of lucency, and apparent physeal widening. (From Whyte MP, Madson KL, Phillips D, et al. Afosfotase alfa therapy for children with hypophosphatasia. *JCI Insight*. 2016;1:e85971, Fig. 2.)

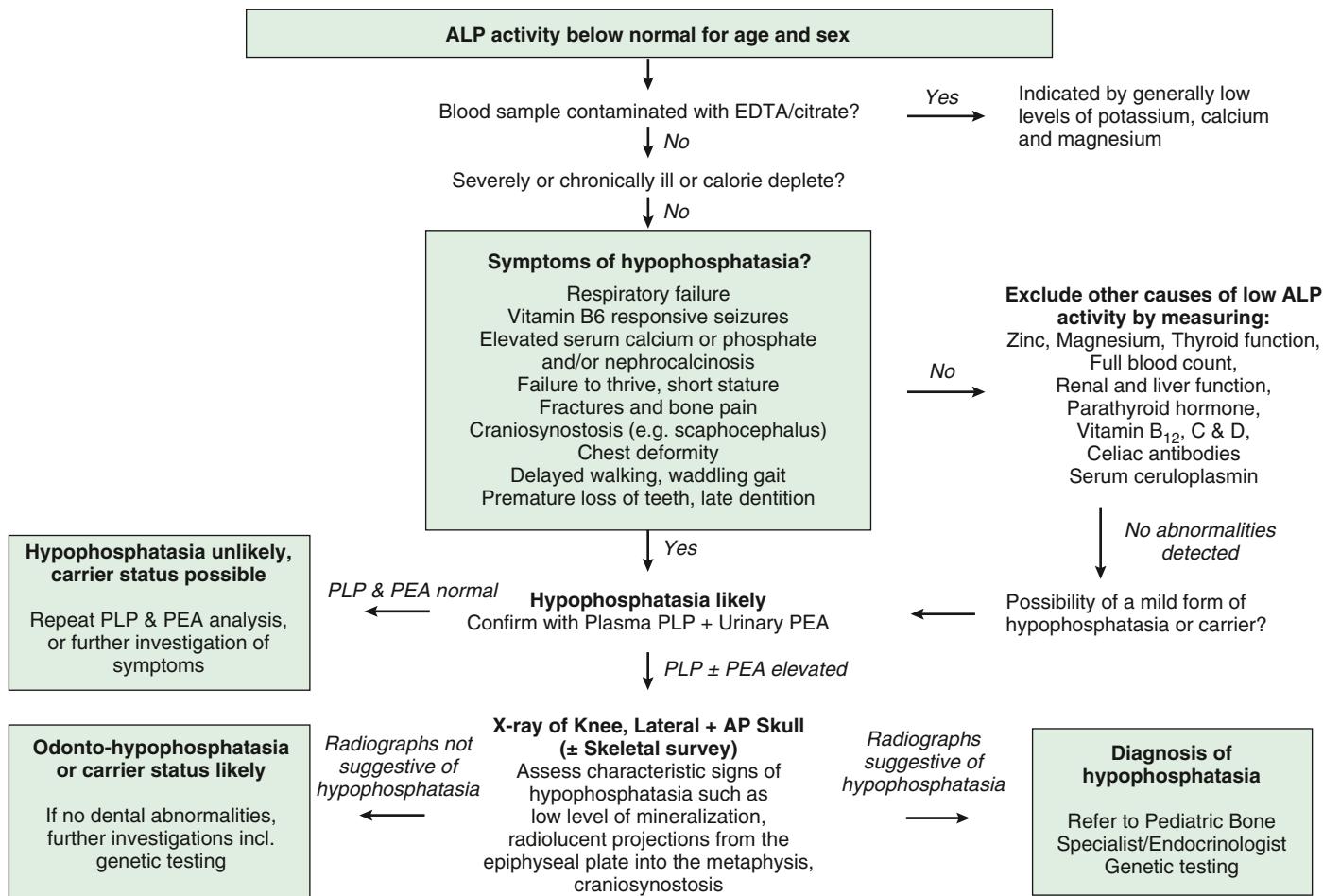


Fig. 747.3 Diagnostic algorithm for the investigation of children presenting with low ALP activity and/or symptoms of hypophosphatasia. For patients with low ALP, other conditions such as nutritional deficiencies (protein/calorie, zinc, folic acid, magnesium, vitamins B6, B12, and C), vitamin D excess, hypothyroidism, hypoparathyroidism, celiac disease, recent significant blood transfusions, renal osteodystrophy, cardiac surgery and cardiopulmonary bypass, posthepatic resection and transplantation, achondroplasia, and Wilson disease need to be excluded. AP, Anteroposterior; PEA, phosphoethanolamine; PLP, pyridoxal-5'-phosphate. (From Saraff V, Narayanan VK, Lawson AJ, et al. A diagnostic algorithm for children with low alkaline phosphatase activities: lessons learned from laboratory screening for hypophosphatasia. *J Pediatr.* 2016;172:181–186. Fig. 3.)

Table 747.2 Causes of Hypophosphatasemia

Cardiac bypass surgery	Milk-Alkali syndrome
Celiac disease	Multiple myeloma
Clofibrate therapy	Osteogenesis imperfecta, type II
Cleidocranial dysplasia	Pernicious or profound anemia
Cushing syndrome	Radioactive heavy metals
Hypophosphatasia	Starvation
Hypothyroidism	Vitamin C deficiency
Improperly collected blood (oxalate, EDTA)	Vitamin D intoxication
Inappropriate reference range	Wilson's disease
Massive transfusion	Zn ⁺⁺ or Mg ⁺⁺ deficiency

EDTA, Ethylenediaminetetraacetic acid

From Whyte MP. Hypophosphatasia: an overview for 2017. *Bone.* 2017;102:15–25.

Table 1.

Some mild HPP forms require only symptomatic and supportive treatment. The primary treatment for more severe HPP is enzyme replacement therapy with recombinant human TNSALP (alsotase alfa). This therapy decreases the mortality rate in prenatal HPP and improves skeletal healing and mineral content, pulmonary status, and overall physical activity in other symptomatic forms.

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Chapter 748

Hyperphosphatasia

Nourah N. Almutlaq and Linda A. DiMeglio

Hyperphosphatasia is a set of conditions characterized by hyperphosphatasemia (elevated serum alkaline phosphatase [ALP]). Increases in alkaline phosphatase are most commonly because of hepatobiliary disease or bone disorders characterized by high osteoblast activity, including nutritional rickets. Distinguishing liver from bone etiologies requires fractionating alkaline phosphatase isoenzymes or measuring bone-specific alkaline phosphatase as well as other laboratory assessments of liver function and bone turnover/vitamin D status. ALP activity varies by age and gender; therefore, specific reference ranges should be employed. It is usually higher in pediatric populations than adults, peaking at times of high bone formation including in the first 6 months and during pubertal growth.

In children younger than 5 years, marked increases in alkaline phosphatase without clinical or laboratory evidence of liver or bone disease is most often because of **benign transient hyperphosphatasemia** generally detected as an incidental finding during screening laboratory evaluations or evaluations performed to assess a specific complaint. The cause may be related to excess sialylation of alkaline phosphatase, which slows clearance. Cases often follow viral illness, including SARS-CoV-2 infection. Serum alkaline phosphatase values as high as 3,000–6,000 IU/L may be encountered. Liver and bone isoenzyme fractions are both elevated; there are no other clinical or laboratory signs of hepatic or bone disease. Diagnosis is confirmed by a careful clinical history plus laboratory assessments of calcium, phosphorus, creatine, AST, ALT, GGT, bilirubin, PTH, and 25-hydroxyvitamin D. A CBC should also be drawn to rule out oncologic processes. Alkaline phosphatase should be followed serially (every 2–3 months) until resolution is documented. The condition usually resolves within 16 weeks without intervention and does not recur.

Juvenile Paget disease (familial hyperphosphatasemia, idiopathic hyperphosphatasia or IHH) is a rare autosomal recessive bone disease hallmark biochemically by marked serum ALP activity elevation. Most cases are because of loss-of-function variants in the tumor necrosis factor receptor superfamily, member 11B gene (TNFRSF11B) that encodes osteoprotegerin (OPG). OPG inhibits osteoclastogenesis and osteoclast activity by preventing receptor activator of nuclear factor κ-B (RANK) ligand (RANKL) from binding to its receptor RANK. Affected children are asymptomatic at birth and gradually develop progressive long bone deformity (including kyphoscoliosis), bone pain, and significant fractures. X-rays show bowing and diaphyseal thickening, along with osteopenia (Fig. 748.1). Radiographically, the bony texture is variable; dense areas (showing a teased cotton-wool appearance) are interspersed with radiolucent areas and general demineralization. Long bones appear cylindrical, lose metaphyseal modeling, and contain pseudocysts that show a dense, bony halo. Children with juvenile Paget disease have short stature, large skulls with a thickened cranium (widened diploë) that may be deformed, and progressive and profound hearing loss. There is substantial phenotype variability; some cases are diagnosed in infancy and others in late childhood. This disorder is distinct from adult Paget disease (osteitis deformans) because bone histology reveals a lack of normal cortical bone remodeling and an absence of the classic mosaic pattern of lamellar bone found in the adult condition. Given the rarity of this disorder, there is no strong evidence surrounding optimal clinical management; however, antiresorptive therapy with bisphosphonates is associated with clinical, biochemical, and radiographic improvement.

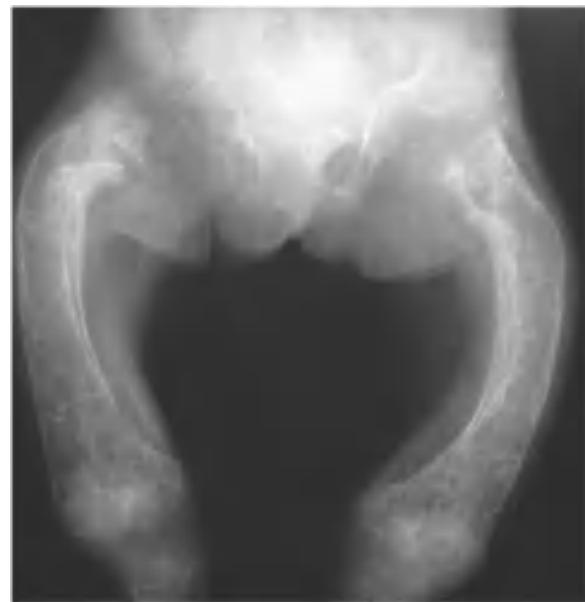


Fig. 748.1 Juvenile Paget disease showing bowing and thickening of the diaphyses and osteopenia. (From Slovis T, ed. Caffey's Pediatric Diagnostic Imaging, 11th ed. Philadelphia: Mosby, 2008. Fig. 167–226, p. 2744.)

Other rare forms of hyperphosphatasia include **expansile skeletal hyperphosphatasia (ESH)** caused by dominant variants in the TNFRSF11A gene encoding receptor activator of RANK, which regulates osteoclastogenesis, and **hyperphosphatasia-mental retardation syndrome** caused by recessive variants in PIGV in the glycosylphosphatidylinositol (GPI)-anchor biosynthesis pathway.

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Chapter 749

Osteoporosis

Rebecca J. Gordon and Catherine M. Gordon

Osteoporosis, the most common bone disorder in adults, is relatively uncommon in children and adolescents; the criteria that underlie this diagnosis in young patients are a source of debate. This disorder is characterized by diminished bone volume and a marked increase in the prevalence of fractures. In contrast to osteomalacia, which shows undermineralization and normal bone volume, histologic sections of bone in all forms of osteoporosis reveal a normal degree of mineralization but a reduction in the volume of bone, especially trabecular bone (vertebral bone). The **diagnosis of osteoporosis in children and adolescents** requires evidence of skeletal fragility with: (1) a clinically significant fracture history, which is defined as at least two long bone fractures in children less than 10 years old, at least three long bone fractures by 19 years old, or any vertebral fractures; and (2) low bone density, with age, sex, and ancestry-matched bone mineral density (BMD) Z-score ≤ -2.0 , assessed by dual-energy x-ray absorptiometry (DXA).