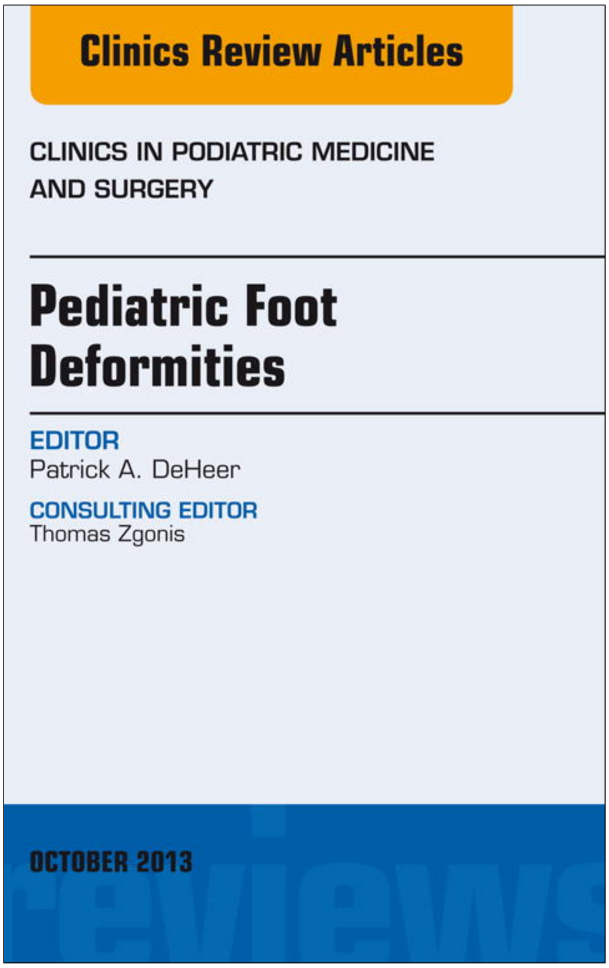
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Principles of Management of Growth Plate Fractures in the Foot and Ankle

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KEYWORDS

• Pediatric fracture • Growth plate injury • Physis fracture • Salter Harris

KEY POINTS

- Physeal injuries are an interesting and challenging group of injuries based on the unique characteristics of skeletally immature bone and the developing pediatric patient.
- Providers who treat pediatric injuries must have a detailed understanding of not only the histologic and mechanical properties of the pediatric skeleton, but also understand and be sensitive to the psychological and social expectations of the patients and their families.
- The provider is challenged to meet the expectations for communication regarding not only the immediate needs of the injured patient, but also the long-term prognosis of the injury.
- Clearly stated goals and limitations of treatments must be given by the provider to gain the trust and compliance of the patient and his or her family. Detailed understanding of the fracture mechanism and fracture patterns is essential for accurate diagnosis and treatment.
- The provider must constantly remain vigilant for expected and unexpected changes in the osseous and soft tissue structures during treatment.
- Failure to recognize signs of growth interruption and progressive changes in position during healing or subsequent years of growth may lead to devastating functional abnormalities.

UNIQUE BONE QUALITIES OF THE PEDIATRIC SKELETON

Understanding the histologic make up of pediatric bone and how this relates to mechanical and healing properties is the starting point in evaluation and management of pediatric fractures. Histologically, woven bone predominates in the skeletally immature patient. Mechanically, woven bone responds differently to external stress than

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compact or lamellar bone found in the mature skeleton. In order to accurately diagnose and manage these fractures, it is imperative that the physician understands the skeletal age of the patient. Certain fracture patterns predominate at various stages of development, and clinical decisions are sometimes based as much on the stage of development as on the fracture pattern. Structurally, woven bone is more porous than lamellar bone. However, the mineral ratio of pediatric bone is the same as compact bone. The ratio of woven bone to compact bone changes during development. Mechanically, pediatric bone has increased capacity for plastic deformation and decreased tendency for comminution when compared with adult bone. When a mechanical stress is placed on the bone, the tendency is to fail in response to compression forces more often than with tension forces. This compression force can result in an incomplete fracture from plastic deformation known as a Torus or buckle fracture. These injuries are commonly seen in children at multiple ages. Another type of incomplete fracture based on the plastic properties of pediatric bone is the greenstick fracture. Unlike the torus fracture, a greenstick has an incomplete fracture on the tension side of the bone. Unless significantly displaced, treatment of a Torus or Greenstick fracture requires only support in a cast or a brace, as these fractures are usually stable. Healing times are usually short, and complications are rare (**Fig. 1**).

The periosteum of pediatric bone is thicker and more robust than in the adult skeleton. It is loosely attached at the diaphysis and tightly adhered to the metaphyseal cortex and the epiphyseal perichondrium. In addition, the periosteal tissues and ligaments are stronger than the adjacent physis and woven bone. Because of these properties, in many pediatric fractures, the periosteal tissues remain intact after fracture. This is important for healing of the fracture; additionally, it can aid in reduction of fractures by providing a tether to hold the fragments in alignment during traction maneuvers used in closed reduction.

Pediatric bone and the periosteum are very vascular and extremely osteogenic, allowing rapid healing. The vascular supply to pediatric bone arrives from multiple sources. Epiphyseal bone blood supply is derived from capsular soft tissue attachments and nutrient arteries that enter the epiphysis and supply both the epiphysis and the germinal layer of the physis. Metaphyseal vascular supply is mainly from endosteal vessels that form capillary loops. These arteries provide vascularization to the portion actively undergoing ossification but do not provide flow to the distal physis. The physis gets its vascular supply from epiphyseal, metaphyseal, and perichondral contributions. It is also important to understand that epiphyseal and metaphyseal blood supplies remain distinct with no vascular interconnection crossing the physis. As in the adult skeleton, the articular cartilage has no independent blood supply. Articular cartilage receives its nutrition from synovial fluid. Cartilage viability is dependent on synovial fluid production and distribution. Fluid production is dependent on active and passive joint motion. Joint motion signals synovial fluid production and also distributes the fluid, and is therefore vital to articular health and preservation of articular anatomy and function. Every attempt should be made to maintain passive and/or active joint motion during recovery. Stable fixation provides a platform for early range of motion and early rehabilitation. Conversely, excessively long periods of casting and immobilization are detrimental to joint health and should be avoided.

PHYSEAL HISTOLOGY

The physis is made up of 3 zones, with multiple layers residing in each zone. The zone nearest the epiphysis is the growth zone made up of the germinal and proliferative layers. This zone is responsible for the longitudinal growth of the bone as cells

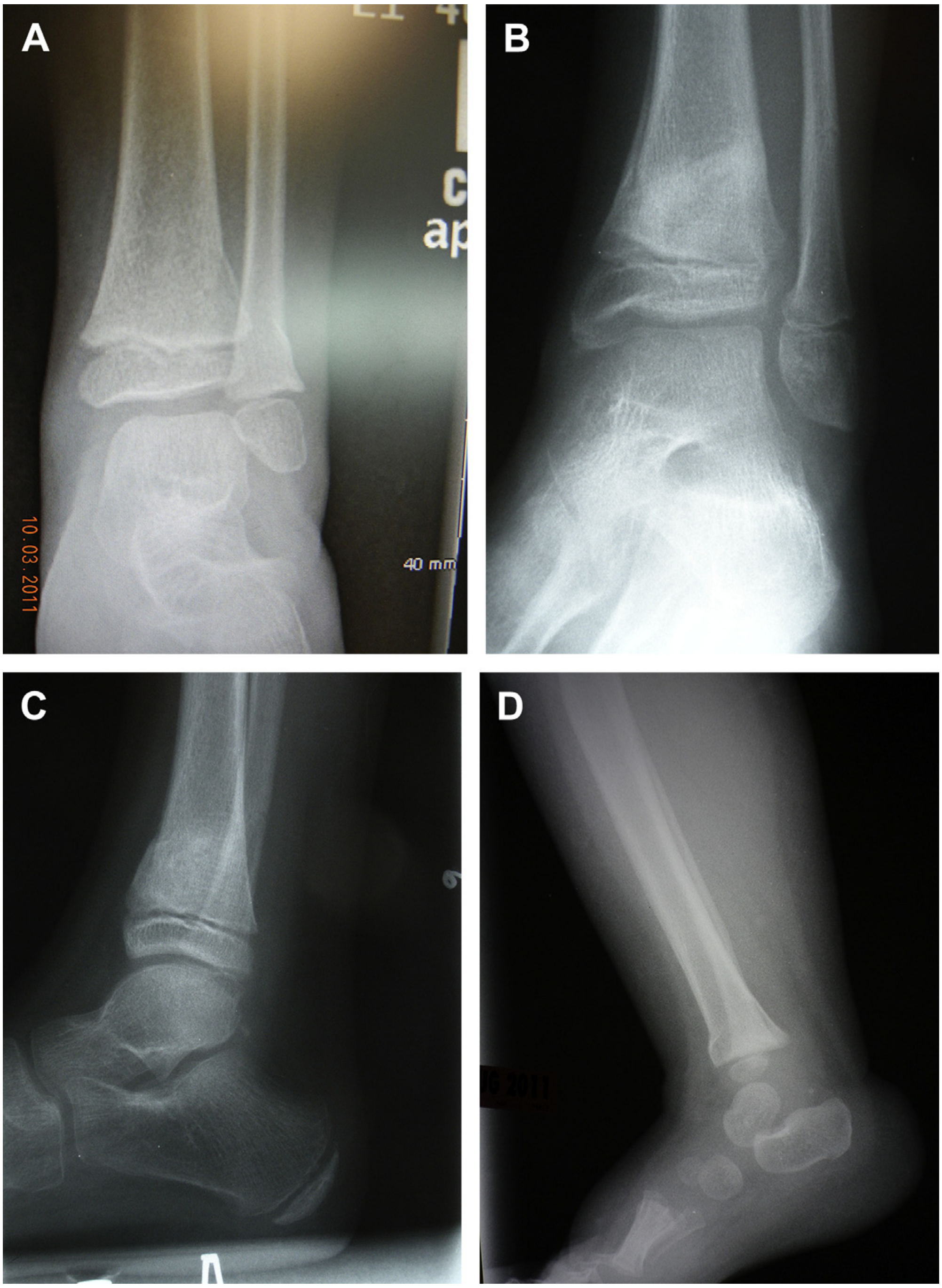

Fig. 1. (*A*) Plastic deformation of tibial and fibular metaphysis. Failure has occurred at the compression side of the bone, designating this as a torus fracture. Minimal displacement of this fracture is noted. Casting is the treatment of choice, and growth interruption is unlikely. (*B, C*) Typical radiographic findings on anterior-posterior (AP) and lateral views during healing of torus fracture of the tibia in an adolescent. (*D*) Buckle or torus fracture of the distal tibia in a young patient. Plastic deformation with minimal displacement requires no reduction. The displacement in this case is minimal and is in the plane of joint motion and therefore should be well tolerated.

move from a resting state in the germinal layer to an area of rapid mitosis and division in the proliferative layer, or layer of columniation.

The second zone is the zone of cartilage maturation, in which resides the hypertrophic layer and layer of calcification. This zone is largely composed of chondrocytes, which enlarge significantly in the hypertrophic layer, disintegrate, and then form a layer of necrotic calcified cells that develop a network of tunnels for the infiltration of osteoblasts and metaphyseal vessels. This zone is the weakest area of the physis and is especially susceptible to shearing, bending, and tension forces. Although this is known to be the weakest zone, it has been noted that 50% of physeal injuries cross multiple zones.

The final zone of ossification or transformation has 2 layers and is closest to the metaphysis. The layers are divided into the layer of vascular penetration and zone of ossification. In these layers, metaphyseal vessels penetrate the layer of calcified chondrocytes. This is followed by osteoblastic activity and subsequent osteogenesis.[1]

The zone of Ranvier is a circumferential groove that surrounds the periphery of the physis. This zone consists of prechondrocytes as well as fibroblasts and fibrocytes. The osseous ring of Lacroix is an extension of the metaphyseal cortex that is present within this zone. This area aids in support of the physis at the weak osteochondral junction and aids in securing the epiphysis to the metaphysis.

As noted previously, physeal vascular supply is from 3 sources, and the vessels are not connected across the physis. Mechanically, physeal tissue is weaker than metaphyseal, epiphyseal, or diaphyseal bone. It is also significantly weaker than ligaments; the ligaments are approximately 2 to 5 times stronger than the growth plate. In response to external forces, the physis is most resistant to traction and least resistant to torsion.

REMODELING

Due to the constantly changing state of pediatric bone, remodeling of a fracture can occur during the remaining period of growth. Limited osseous adaptation and improvement in position and function are possible. In some circumstances, less than perfect anatomic reduction in the acute setting may be acceptable. For example, angulation of long bone fractures may improve over time secondary to input from external forces. There are limitations to this concept however; angulation of more than 15° is not acceptable, and as the angulation approaches 90° to the plane of motion of the segment, remodeling is less likely. Additionally, if a displaced fracture crosses the physis at 90°, remodeling is not likely.

There are circumstances in which remodeling will not occur. Intra-articular fractures should be accurately reduced in all cases. Acute shortening will not improve with growth and development. Shortening should always be addressed during initial or subsequent reduction attempts. Axial rotation is also a circumstance in which remodeling is not possible. It should be emphasized that the younger the child, the more likely remodeling is to occur. If the child has less than 1 to 2 years of growth remaining, remodeling should not be relied upon, and the physician should obtain accurate reduction.

PHYSEAL INJURY MANAGEMENT

Before deciding on a course of treatment and before making recommendations regarding care of a pediatric patient, a detailed evaluation of the patient with thorough history and physical examination should done. Medical conditions along with associated vascular, neurologic, rheumatologic, and soft tissue concerns must be addressed in the treatment plan. Next, radiographic examination should be focused on the injured anatomic zone and any possible associated injuries. For extremity trauma, a minimum of 3 planar views should be obtained. Complicated or intra-articular fractures should be evaluated with computed tomography (CT) scans with additional multiplanar reconstructions. Comparison radiographs of the uninjured extremity can be very useful to determine normal anatomy and pick up subtle fractures or dislocations. Stress views are needed in certain injuries that carry expected instability. When evaluation of the patient and fracture injury has been assessed, closed reduction is typically attempted with consent from the patient and family to proceed to open reduction if closed reduction is not possible. There are certain fractures in which closed reduction is not practical or possible. In these cases, primary open reduction internal fixation (ORIF) should be chosen and unnecessary closed reduction attempts avoided. If a fracture cannot be maintained with splintage, such as with distal forefoot fractures, attempts at reduction should be avoided to prevent further damage to the growth plate and associated structures. Similarly, if a reasonable attempt at closed reduction fails, multiple attempts at forced closed reduction should be avoided to prevent further injury.

Both closed reductions and open reductions need to be performed with a measured amount of force to prevent further damage to the physis that could result in destruction of the germinal layers. With closed reduction, more focus should be placed on traction rather than forceful manipulation of the fracture fragments. Due to the robust nature of the pediatric periosteum, ligamentotaxis many times will produce anatomic reduction. For closed reductions, the patient should be sedated or anesthetized to prevent pain and provide relaxation of the extremity. Muscle spasm and tense muscle compartments will prevent reduction and will make appropriate casting extremely difficult. Radiographs should be repeated immediately after reduction and at intervals during recovery to ensure adequate reduction is maintained.

Surgical principles begin with careful tissue handling and dissection technique to preserve blood supply. Priority should be given to indirect reduction techniques and percutaneous fixation when possible. During ORIF, every effort should be made to limit growth center damage with overzealous exposure and tissue stripping. For instance, the surgeon should not disturb the physeal periosteum and peri-fracture soft tissues. Principles of physeal injury fixation focus on prevention of further damage to the physis and growth interruption. When necessary, pins can be temporarily placed across the physis to engage and stabilize epiphyseal or metaphyseal fractures. However, only smooth pins should cross the physis, and these should be removed as soon as practical. Additionally, parallel pins are safer than crossed pins, and screws or other fixation techniques producing compression should not traverse the physis. Repeat radiographic examination should take place every 6 to 12 months after fracture healing until growth is completed to assess for any growth disturbances.

CASE STUDIES

The most utilized classification system used in pediatric fractures is the Salter-Harris classification. There are 5 types originally noted, which are based on the location of the fracture or fractures distal and proximal to the physis. There are further subgroups that have been added to the original classification system, which describe unique circumstances. Understanding of this classification system is very helpful in determining proper treatment and assessing long-term prognosis.

Type 1

This fracture pattern is defined by a slip through the physis only and tends to occur in younger children. Because of its strength, the periosteal hinge usually remains intact. These fractures have a good prognosis for healing and a low incidence of epiphysiodesis. Keep in mind that these fractures may not be visible on radiograph; therefore, a high degree of clinical suspicion and a thorough physical examination are important.[2]

Treatment consists of closed reduction if displaced and splintage with a cast or brace. In the first 3 weeks, weight-bearing status is determined based on the fracture site and propensity for displacement. Once clinical signs of recovery including decreased pain and improved range of motion are noted, the patient can be transitioned to a weight-bearing cast or walking boot for an additional 3 weeks. Radiographic findings such as fracture gap filling and extensive callus may signal physeal growth interruption. Healing is usually rapid, especially in younger patients, and growth interruption is typically unlikely in this injury pattern (**Figs. 2** and **3**).

Type 2

This fracture pattern is the most common physeal injury. In this group, a transverse slip of the physis, along with a fracture through the metaphysis, is evident. This fracture pattern is more commonly seen in children over 10 years of age.[3] If stable and not significantly displaced, this injury may be treated with closed reduction with external splinting. Prognosis for healing is good, with a low incidence of growth interruption. Significantly displaced fractures that cannot be closed reduced or that remain unstable following reduction require fixation. The importance of careful handling of the soft tissues and gentle reduction techniques can not be overemphasized to prevent further

Fig. 2. Type 1 injury of the distal fibular physis. The displacement within the physis is subtle, and there is no fracture of the epiphysis or metaphysis. Clinical examination is extremely important for diagnosis. Treatment is with splint or cast, with modified weight-bearing to prevent further displacement. Growth disturbance is unlikely, and healing is usually rapid. Physeal injuries of the ankle are the second most common growth plate injury following wrist fractures.

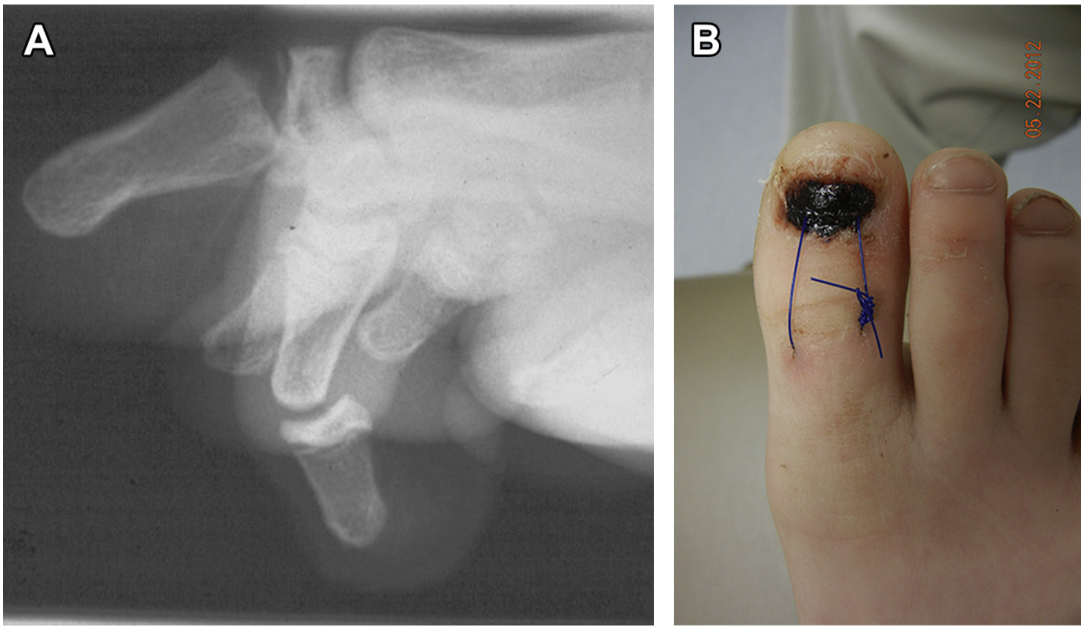

Fig. 3. (*A*) Type 1 physis fracture of the hallux. (*B*) Dorsal suspension technique to stabilize physeal fracture of the phalanx with large nonabsorbable suture through the nail bed and the extensor tendon. This technique is done using digital local anesthesia in the clinic or emergency room setting, avoiding the need for pinning or admission for operation. Strong plantar periosteum aids in reduction following dorsal tension of the suture.

damage to the growth plate and the periosteum. Inability to reduce the fracture or persistent gap of the physis may indicate that the periosteum is interposed in the physis and is an indication for ORIF. The authors always recommend obtaining radiographs of the contralateral extremity for comparison of physeal thickness and normal anatomic landmarks. This can prove invaluable for guidance in anatomic reduction (**Figs. 4–7**).

Type 3

This fracture pattern consists of a transverse physeal slip with a vertical fracture through the epiphysis. This is an intra-articular fracture at higher risk for growth disruption and arthrosis. CT scans are recommended to identify displacement and to plan for reduction. As with all intra-articular fractures, ORIF for accurate anatomic alignment and stability is recommended followed by appropriate splintage. As discussed previously, stable fixation and early range of motion should be the goal, and excessive periods of immobilization should be avoided (**Fig. 8**).

Type 4

This fracture pattern is a transverse slip through the physis and vertical fracture through the metaphysis and epiphysis. The management of this fracture pattern and the associated risks are the same as for type 3. ORIF is usually needed for anatomic reduction followed by appropriate splintage. Careful radiographic monitoring should be pursued after injury to assess for growth interruption and progressive angular deformity, which are higher in this fracture type.

Type 5

This injury pattern involves a compressive crush of the physis caused by an axial load through the epiphysis. There is no transverse slip of the physis and no visible metaphysis or epiphysis fracture on radiograph. This compression injury has a high risk of

Fig. 4. Type 2 injury of the proximal first metatarsal. Note the displacement of the physis with fracture through the metaphysis.

growth interruption because of direct damage to the physeal cells. Treatment includes protected weight bearing and, most importantly, careful follow-up to identify growth interruption or progressive angular deformity.[4] Advanced techniques such as physeal debridement and reconstructive osteotomy may be required if progressive deformity results from growth interruption. The younger the patient is at the time of injury, the higher the risk of progressive deformity or limb length inequality. Older children have less time of growth remaining and therefore lower likelihood that progressive deformity will occur. Complications of this type and all other types of growth plate injury may result in the need for limb or bone segment lengthening in cases of significant deformity.

Type 6

One of the newer additions to the Salter-Harris classification is the Rang type 6 fracture. This fracture pattern follows a blunt trauma injury. The result is direct insult in which there is an injury to the perichondral ring with traumatic removal of physeal material. This injury is sometimes associated with lawnmower accidents, in which the rotary blade damages soft tissue and a portion of the peripheral physis.[5] Radiographic findings are widely varied but may be distinguished by the presence of a metaphyseal or epiphyseal fracture fragment within the periphery of the physis or obvious loss of the physeal and adjacent bone structures. Resulting callus from the bone and physeal injury makes the victim prone to asymmetric osseous bridging of the physis. This osseus bridging often leads to a progressive angular deformity due to partial physeal closure.[1]

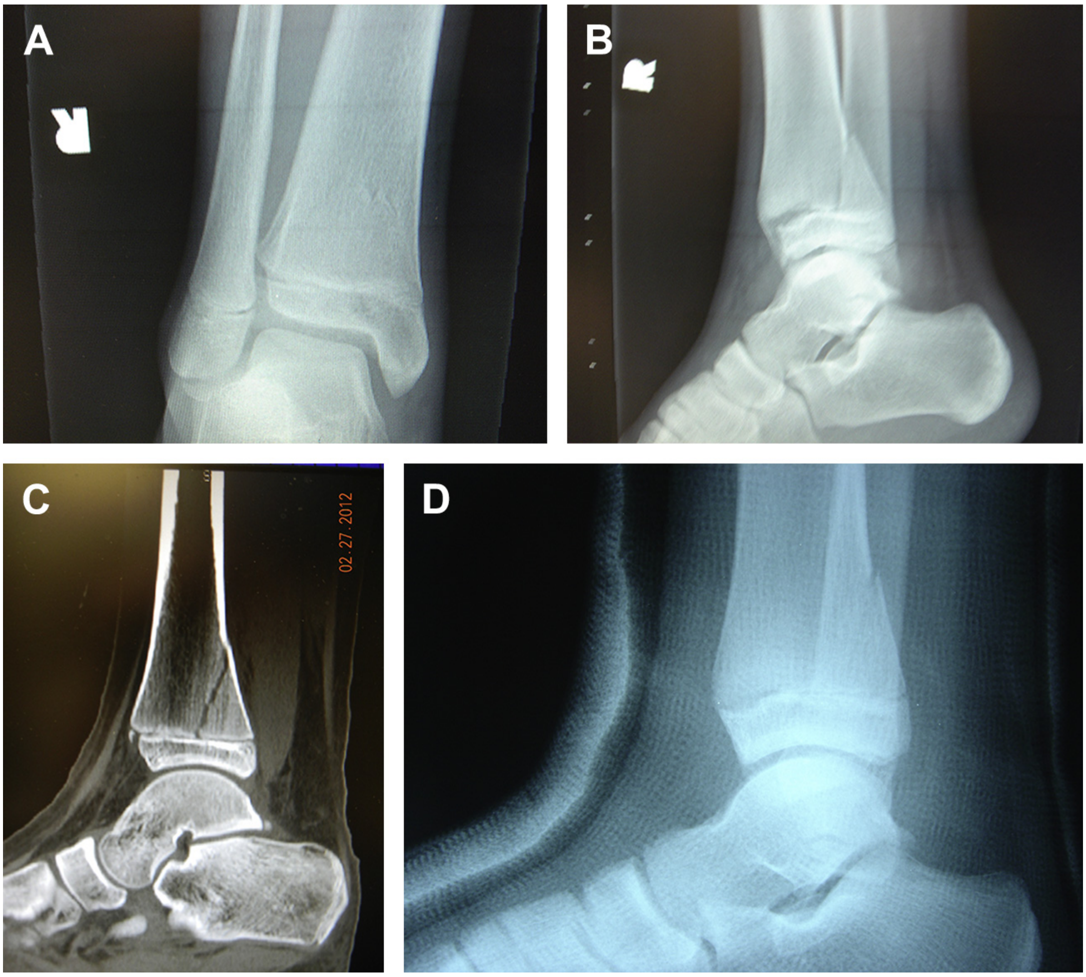

Fig. 5. (*A*) Type 2 injury of the distal tibia. AP view shows subtle signs of metaphyseal fracture. The slip of the physis is not visible on the AP view. These fractures are most common in the adolescent years. (*B*) Lateral view clearly showing the slip through the physis with displacement. (*C*) CT scan clarifies the fracture pattern and extent. Advanced imaging is recommended for most articular injuries and can aid in decision making for treatment. (*D*) Recommended treatment is closed reduction with casting. Thick periosteum in the pediatric patient aids in reduction and maintenance of fracture position with distraction and casting. Growth interruption is not common with this type of injury.

In cases of open trauma, treatment can be complicated due to the multiple variables. As with any open fracture, one should treat open pediatric fractures with careful systemic evaluation, appropriate antibiotics, and tetanus prophylaxis as indicated. This is followed by irrigation and meticulous debridement of devitalized tissue and foreign material.[6] Attention to stabilization of the soft tissue envelope, as well as the bone segments, is vital in open injuries. External fixation techniques can be invaluable to provide stability and allow access for debridement and reconstruction of both the soft tissue and the bone (**Fig. 9**).

TRANSITIONAL FRACTURES

The juvenile Tillaux and triplane fractures are classified as transitional fractures because of their occurrence in the period between adolescence and skeletal maturity, at which time the physis undergoes final closure. This transitional period is an approximately 18-month window when the distal tibia physis closes, and it usually starts at ages 12 to 14 years. The pattern of physeal closure proceeds from central, to

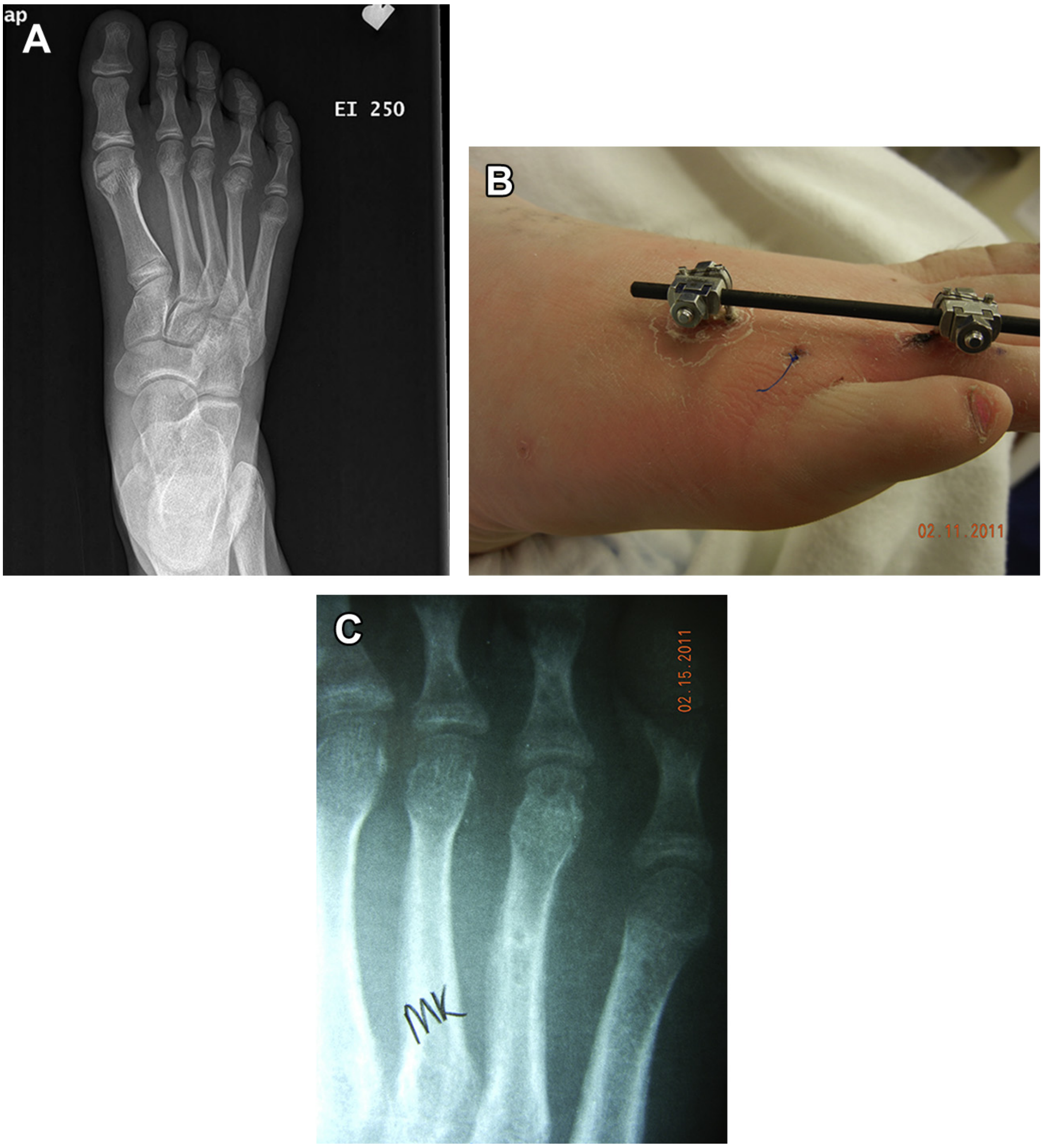

Fig. 6. (*A*) Type 2 of the distal fourth metatarsal. Significant displacement through the physis with subtle fracture of the metaphysis is evident. (*B*) External fixation was utilized for distraction and maintenance of the fracture position. External casting would not provide adequate stability in this location, and the fragments were too small for internal fixation. Fixator was minimally invasive and preserved the articular structures. (*C*) Result after reduction and healing of the fracture. The authors have used this technique successfully in a variety of pediatric peri-articular fractures including Frieberg infraction. Reduction and stabilization can be achieved with minimal additional soft tissue damage. In addition, the arthrodiastasis effect of the frame unloads the joint surfaces and the physis, allowing for consistent and rapid healing.

anteromedial, to posteromedial, and finally to lateral.[3] The process of medial physeal closure preceding lateral closure directly lends itself to the injury pattern observed during triplane and juvenile Tillaux fractures.

Juvenile Tillaux Fracture

The biplanar fracture of Tillaux is an avulsion fracture that occurs when the lateral aspect of the distal tibial epiphysis is pulled off by the intact distal tibiofibular ligaments. This mechanism of injury gives it a Salter-Harris type 3 fracture pattern. These

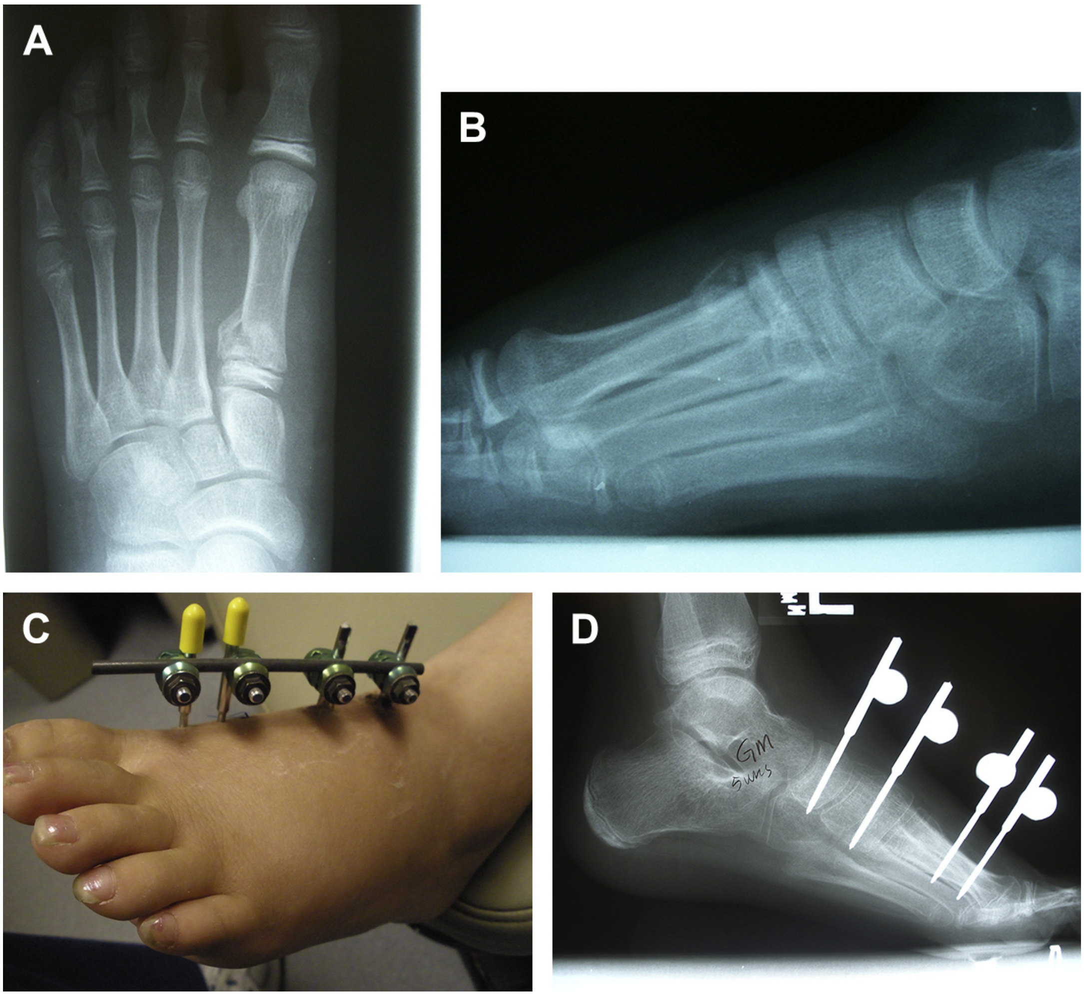

Fig. 7. (*A*) Type 2 of the proximal first metatarsal. Maintenance of reduction in this location is difficult with casting alone, and peri-articular location makes ORIF problematic. (*B*) Lateral view showing unacceptable displacement in the sagittal plane. (*C*) External fixation facilitates reduction and maintenance of position. Further damage to the physis, periosteal, and articular tissues is avoided. (*D*) Lateral view after reduction.

Fig. 8. Type 3 injury to the distal tibial physis. Degree of displacement is difficult to assess on plain film radiographs. CT scanning is recommended for all intra-articular fractures. This fracture pattern requires accurate reduction and stabilization, usually with ORIF.

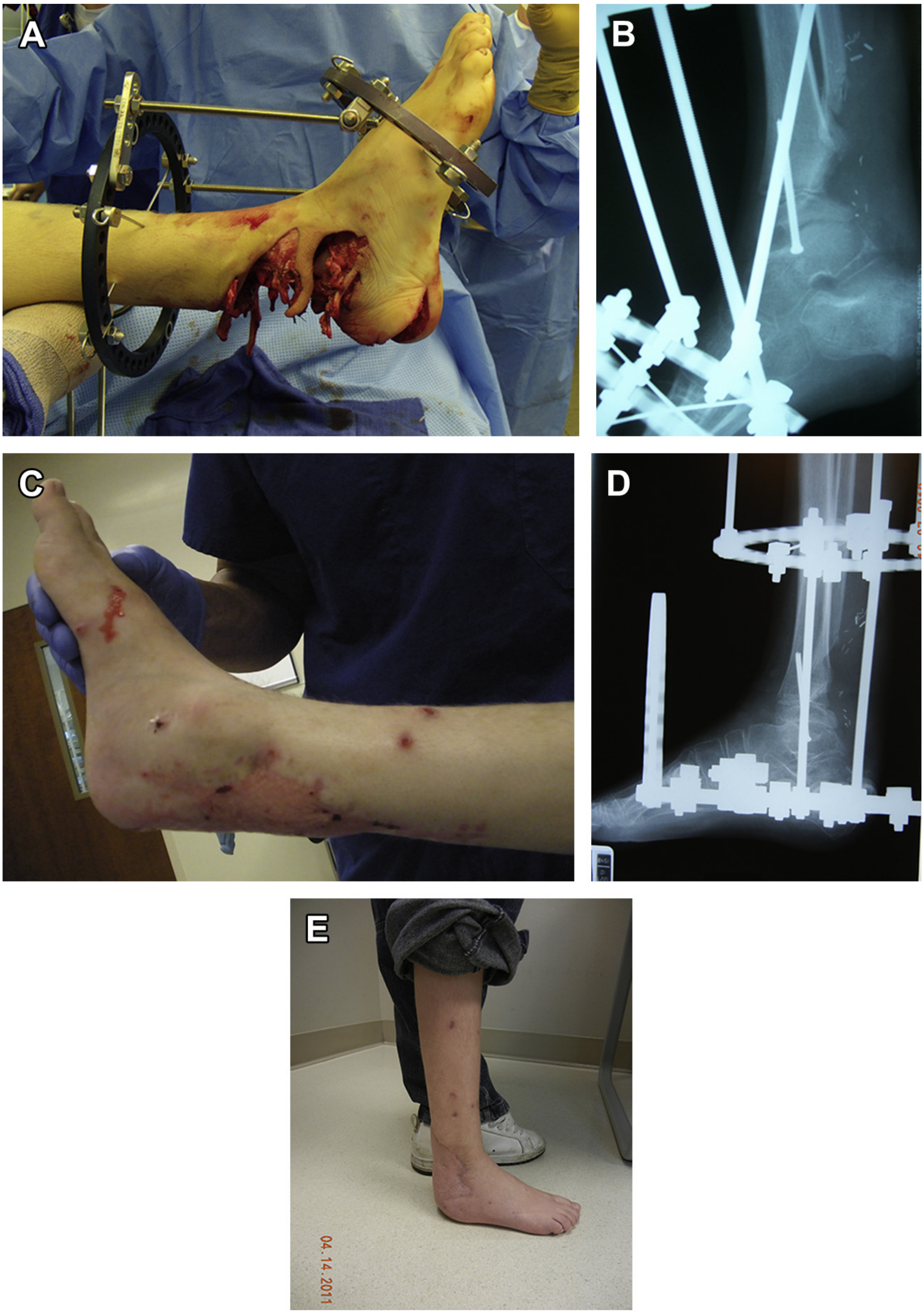

Fig. 9. (*A*) Lawn mover injury in 10-year-old child. Extensive soft tissue loss and bone fracture were sustained. External fixation provided stabilization of the soft tissue envelope and bone segments. The fixator facilitated access to tissues for wound care and soft tissue reconstruction. (*B*) Type 6 injury with extensive loss of the physeal tissues. (*C*) The original fixator was maintained throughout multiple operations for soft tissue reconstruction with ultimate free tissue transfer. The original fixator was removed after the soft tissues were healed. (*D*) Arthrodesis of the ankle and epiphsiodesis was required to halt progressive deformity from growth interruption of the physis and loss of the distal fibula. (*E*) Final result after limb salvage. Patient has partial sensation to the plantar foot and has stable well aligned ankle and foot with intact soft tissue envelope. Due to remaining growth potential at age 10, the patient may require limb lengthening in the future.

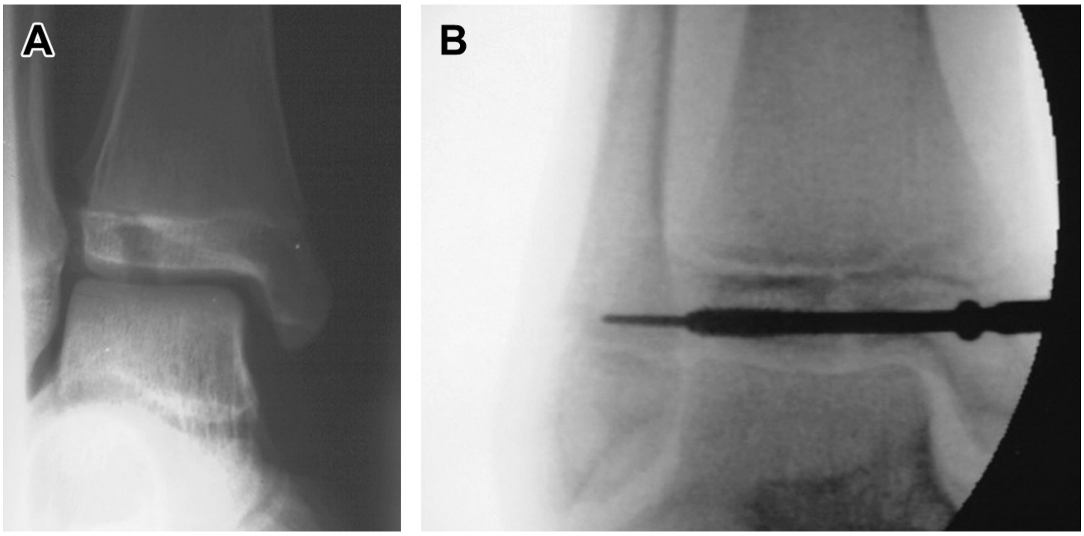

Fig. 10. (*A*) Juvenile Tillaux fracture. This represents a Salter Harris III fracture pattern in the transitional period of development. Because this fracture is intra-articular, careful assessment of displacement should be made with multiple radiographic views and CT scan. (*B*) Intraepiphyseal reduction technique utilizing cannulated screw. The fixation does not enter or cross the physis, so removal is typically not necessary.

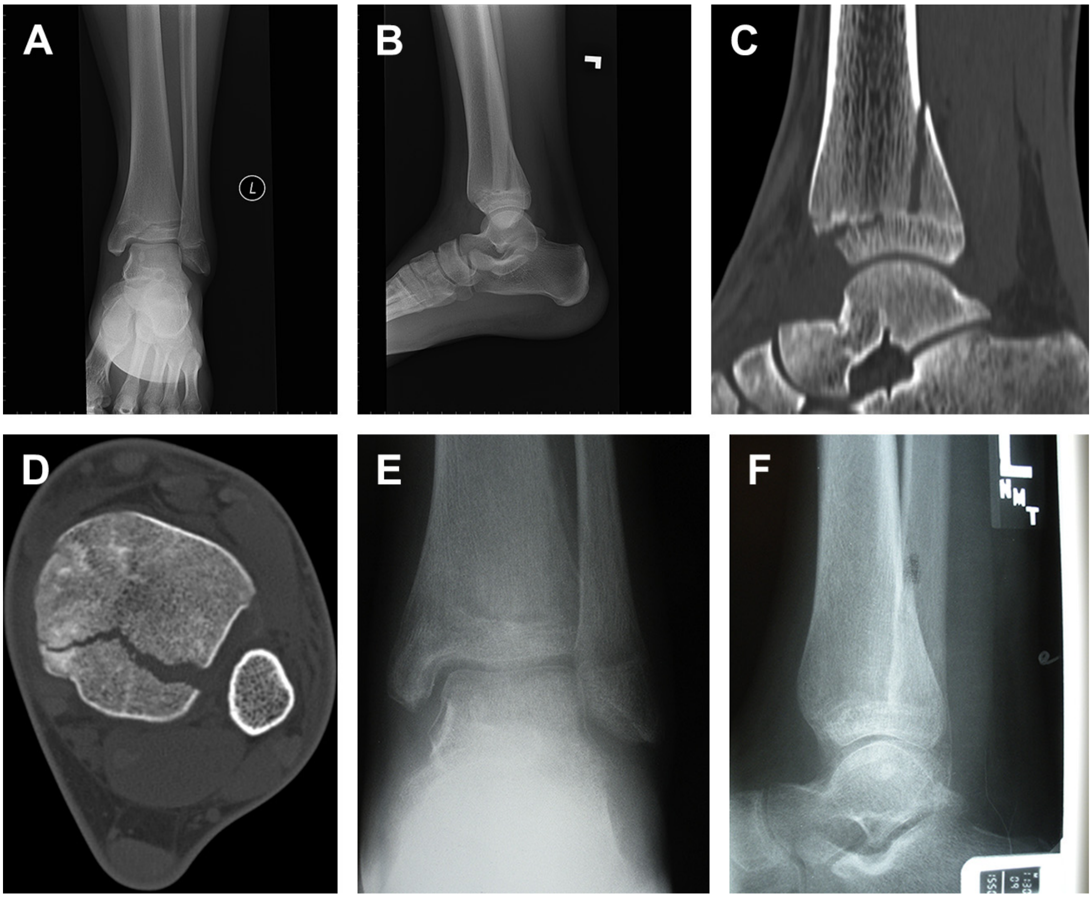

Fig. 11. (*A*) AP radiograph of triplane fracture. The type 3 fracture is easily visible. The type 2 metaphyseal fracture is present but is subtle on this view. (*B*) Lateral view showing typical physeal displacement and typical metaphyseal fracture orientation. (*C*) CT view showing sagittal displacement of the tibia. (*D*) Minimal displacement of the epiphysis fracture is noted on CT scan. (*E, F*) Closed reduction under general anesthesia was accomplished, and a long leg cast was placed to maintain reduction. Because minimal epiphysis displacement was present, closed reduction resulted in good position and healing.

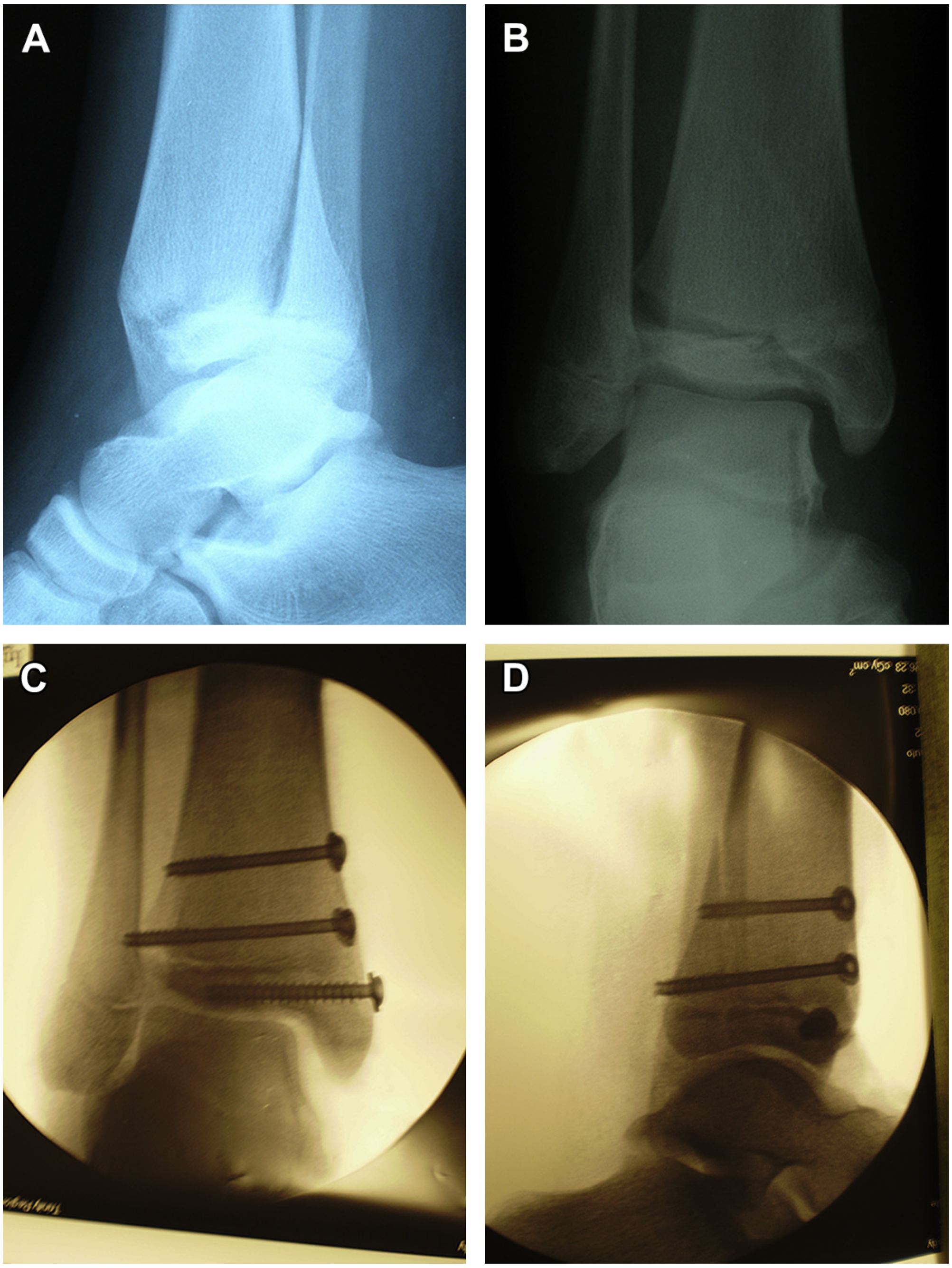

Fig. 12. (*A*) Lateral view of displaced triplane fracture. The transverse plane physeal slip and the frontal plane metaphysis fracture are visible. (*B*) AP view showing the third plane of injury in the sagittal plane. (*C, D*) Open reduction and internal fixation using recommended fixation placement to stabilize all 3 components of the fracture. Stable fixation will allow for early range of motion to preserve joint function and speed rehabilitation.

fractures are comparable in location to the adult Tillaux Chaput fracture, which shares a similar mechanism of injury. The fracture itself is not full-thickness anterior to posterior, and it occurs during the transitional period when only the lateral physis has yet to fuse.[3] In a retrospective study of 237 pediatric ankle fractures, Spiegel and colleagues[7] reported that only 6 (2.5%) were juvenile Tillaux fracture types. These cases occurred at an average patient age of 13 years and 5 months.

The overall outcome after juvenile Tillaux fractures is good, with rare occurrences of angular deformity and minimal risks of growth discrepancy. However, the risk for osteoarthritis is high if articular step-off remains after treatment; therefore, the clinician should carefully evaluate the amount of displacement before and after reduction.[3]

Nondisplaced and minimally displaced fractures may be treated with immobilization in a long or short leg cast. However, ORIF is often necessary because of the intra- articular nature of the fracture. It is important to remember that compressive fixation elements used during ORIF should not enter or cross the physis. Postoperatively, the patient should remain nonweight-bearing in a cast for 3 weeks followed by an additional 3 weeks in a walking cast or brace. A stable fracture construct will allow for early range of motion, which is desirable to preserve articular soft tissue function (**Fig. 10**).

Triplane Fracture

Consistent with transitional fractures, the triplane fracture occurs as a result of relative weakness of the anterolateral tibial physis. Typically, triplane fractures occur approximately 1 year later in boys when compared with girls. As with all transitional fractures, this is attributed to the age difference of physis closure. The injury is a result of external rotation forces, and there is an associated fibular fracture seen in up to 50% of cases.[8] As the name would suggest, the triplane fracture always contains a fracture element in each of the 3 cardinal body planes, and fractures are evident in the epiphysis, metaphysis, and the physis.[9]

When evaluating these fractures on plain film, it is important to assess multiple views. The triplane fracture may appear as a type 3 fracture or Tillaux fracture on the anterior-posterior (AP) view. However, evaluation of additional views will reveal a type 2 fracture on the lateral view. The transverse component of the fracture connects the sagittal and coronal fractures as it traverses the physis.[3]

When planning for treatment, these injuries must have accurate radiographic diagnosis. This is optimally performed with a CT scan using multiplanar reconstructions for more accurate assessment of the amount of displacement and the extension of fracture lines.[10] Treatment of a displaced epiphyseal fracture requires ORIF. The postreduction regimen follows that of type 3 and 4 fractures. There is little risk of subsequent growth abnormality or progressive angulation from this fracture, because physiologic closure is already occurring. Additionally, little growth remains at this anatomic site (**Figs. 11** and **12**).

SUMMARY

Because of the unique histologic and mechanical properties of the pediatric skeletal and physiology of the physis, pediatric growth plate fractures cause pose a challenge for the treating physician. It is imperative that these characteristics be taken into account and the physician have a thorough understanding of the pediatric bone and healing properties, which vary significantly from mature bone. With a thorough understanding, clearly stated goals and limitations of treatment explained to the patient and parents, and institution of appropriate treatment, the care of these patients can be extremely rewarding.

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