Motorized Intramedullary Nail for Management of Limb-length Discrepancy and Deformity

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Abstract

Distraction osteogenesis has been used for more than 50 years to address limb-length discrepancy and deformity. Intramedullary fixation has been used in conjunction with external fixation to decrease the time in the external fixator and prevent deformity and refracture. A new generation of motorized intramedullary nails is now available to treat limb-length discrepancy and deformity. These nails provide bone fragment stabilization and lengthening with reliable remote-controlled mechanisms, obviating the need for external fixation. Motorized intramedullary nails allow accurate, well-controlled distraction, and early clinical results have been positive.

The primary indications for bone lengthening and deformity correction are congenital limb-length discrepancy (LLD) and posttraumatic conditions such as malunion and growth arrest. Distraction osteogenesis has been successfully used to lengthen bone for more than 50 years.[1,2] Achieving the optimal rate and rhythm of distraction is critical to successful distraction osteogenesis, and external fixation has been a reliable tool for this purpose.[1,2] However, the disadvantages of external fixation frames are well known, including the risk of pin tract infections, skin pain, soft-tissue tethering, and joint stiffness.[3-5] Bone lengthening with a fully implantable device is desirable to avoid the complications associated with external fixation; however, mechanical integrity and accurate control of distraction are mandatory. New motorized remote-controlled intramedullary (IM) nails have recently become available and can be used internally to lengthen the femur and tibia.

Background

The use of IM fixation with Rush rods was proposed to supplement external fixation and prevent deformity development during lengthening.[6] Other hybrid techniques have been developed, including lengthening over an IM nail[5,7,8] and lengthening and then nailing.[3] Both of these techniques allow removal of the frame after the distraction phase and decrease the likelihood of refracture.

The ideal device for limb lengthening is an IM nail capable of both bone fragment stabilization and lengthening, which obviates the need for external fixation altogether. Bliskunov[9] described the first such device, which consisted of an IM femoral rod that was attached through an articulated connection rod to the iliac wing, with distraction performed with a ratchet mechanism. Two devices were subsequently introduced: the Albizzia nail (DePuy)[10] and the IM skeletal

kinetic distractor (ISKD; OrthoFix).[11] However, only the ISKD has been approved by the US FDA. Both devices require intermittent axial rotation of the limb to affect distraction. The Albizzia nail and the ISKD consist of unidirectional telescopic distraction rods that are activated by rotation of the limb segment. The Albizzia nail has a ratchet assembly that requires approximately 15° of rotation to effect incremental distraction. The ISKD has a clutch mechanism requiring a smaller amount of rotation between the rod components (3° to 7°) to affect distraction. Control of the rate and rhythm of distraction is inconsistent, which led to some nails activating too fast or too slow, and activation is sometimes quite painful.

The Fitbone nail (Wittenstein intens)[12] employs an electric motor imbedded in the telescopic rod that is activated by intermittent transcutaneous transmission of radiofrequency waves to an implanted antenna/receiver that converts these waves into an electrical impulse that is discharged via a connecting cable. The antenna/receiver is placed subcutaneously (palpable under the skin) and is connected to a motor in the IM nail by a silicone cable running from the antenna/receiver into the base of the nail. Distraction occurs only when the transducer is placed directly over the antenna/receiver, which allows for control of the rate and rhythm of distraction. This device has not been approved by the US FDA and is not currently available in the United States.

The PRECICE nail (Ellipse Technologies) was introduced in 2011. The telescopic rod has a magnetic actuator drive mechanism that is activated by a handheld external electromagnetic activator. Similar to the Fitbone nail, the surgeon controls distraction by programing the controller. The rate of Fitbone distraction is controlled by the number of radiofrequency activations (27, typically divided into three sessions of nine pulses, lasting about 90 seconds) transmitted to the antenna/receiver, effecting approximately 1 mm of distraction. The rate of distraction (or compression) is controlled by the duration of electromagnetic activation of the magnetic motor, programmed by the surgeon into the activator. However, the PRECICE nail has several significant advantages over the Fitbone nail: it can be lengthened or shortened, does not require a cable or subcutaneously imbedded antenna/receiver, and it has been approved by the FDA.

Surgical Approaches

Preoperative radiographic studies should include a full-length AP standing radiograph of both legs, with a lift used to accurately measure and localize the difference in length. A lateral standing radiograph of the femur and tibia also should be obtained. All radiographs should be made with a magnification marker to facilitate accurate measurement of the length and diameter of the femur and tibia. The LLD should be assessed in terms of location, with the discrepancy superior to the knee (femur) considered separate from that inferior to the knee. Differences in foot height can be considered together with the tibia.

The anatomic sites for bone lengthening are in the femur and/or tibia. In general, the bone with the deformity/shortening is approached. If there is a contraindication for surgery in one bone, the other long bone may be approached, but this would result in uneven knee heights. In the femur, there are three approach options: antegrade via a pirifomis entry, antegrade via a trochanteric entry, and retrograde via the knee. In the tibia, the antegrade approach via the proximal tibia is used.

Antegrade Femur

Indications and Planning

This approach is indicated for patients with a femoral LLD who have an open IM canal with a diameter large enough to fit the IM nail. Angular deformity with the apex from the proximal metadiaphyseal femur to the mid diaphysis and rotational deformity can be corrected acutely using this approach. In adults, a piriformis entry can be used. In adolescents, a trochanteric entry should be used to avoid injury to the blood supply of the femoral head.

The level of the osteotomy is planned preoperatively and should be performed at the apex of the deformity in the coronal and sagittal planes (Figure 1). The IM nail is straight (ie, no anterior bow as in trauma nails) and will correct angular deformity after the osteotomy is done at the apex of the deformity. The nail length is chosen to ensure there is adequate stability after lengthening, with at least 5 cm of the thick part of the nail remaining in the distal segment at the end of distraction.

Surgical Technique

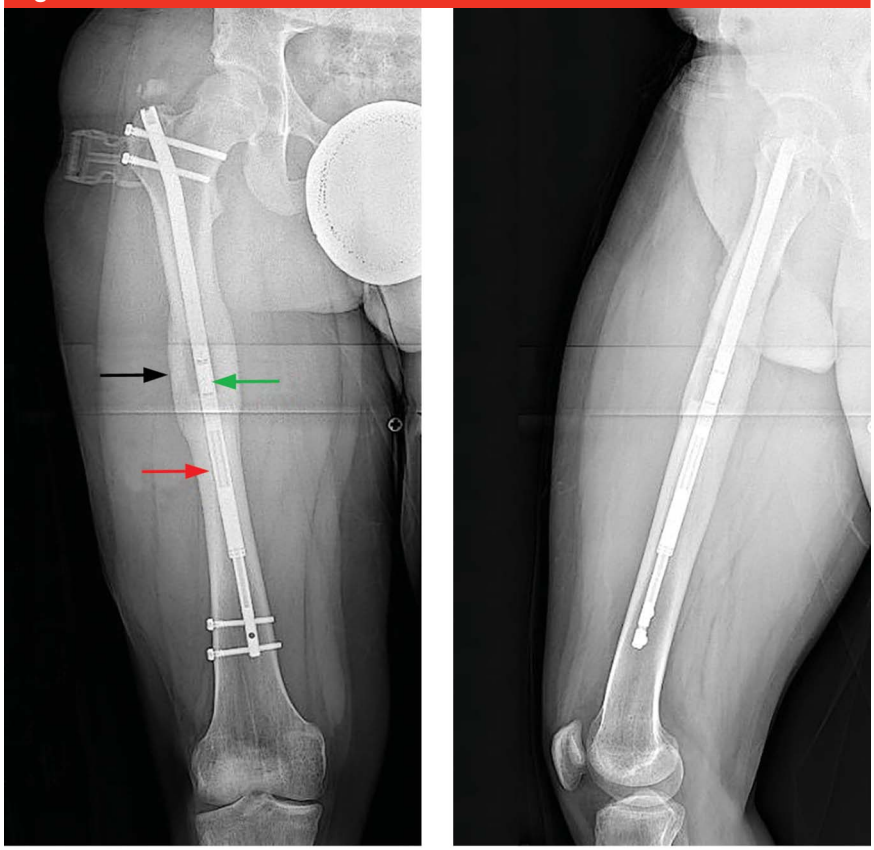
The patient is positioned supine on a flat radiolucent table and a bump is placed under the ipsilateral buttock. Split sheets are used to drape the surgical extremity and provide adequate exposure of the buttock. The C-arm is positioned on the opposite side.

At the planned osteotomy level, a 1-cm incision is made, and the periosteum is elevated to make a pocket for the reamings. Multiple drill holes are made in a transverse fashion. This first step of the osteotomy also serves to vent the IM canal. The hip is adducted and a guidewire is inserted into the canal through the piriformis fossa or greater trochanter. A 3-cm incision is made over the guidewire and a soft-tissue protector is inserted. A cannulated drill is passed over the guidewire

to enter the IM canal. The drill is then replaced with a long, beaded, flexible guidewire, which is inserted into the canal to the distal end of the bone. Flexible reamers are used to ream the IM canal 2 mm larger than the diameter of the nail. The reamings exit through the drill (vent) holes. Steinmann or temporary external fixation pins are placed in the proximal and distal bone segments away from the nail tract to mark rotation. The motorized IM nail is then inserted just proximal to the osteotomy site. An osteotome is used to complete the osteotomy, and the nail is passed across the osteotomy site, correcting any angular deformity. The femur is rotated around the nail to ensure that the osteotomy is complete.

Distal locking screws are inserted first using a freehand technique. The optimal rotation is set, and the proximal interlocking screw is inserted via the jig. The order that the locking screws are inserted is at the discretion of the surgeon. However, the benefit of inserting the proximal locking screw through the jig after the distal screws have been inserted is that the optimal rotation is set without the challenge of freehand insertion of the distal screws. Iliotibial band release can be performed at this point; however this step may be omitted for femoral lengthening <2 cm.

Figure 1



A B

AP (**A**) and lateral (**B**) radiographs of the femur in a 16-year-old boy with congenital limb-length discrepancy. **A,** The femur was lengthened 4 cm (black arrow) using an antegrade trochanteric approach, with the osteotomy performed at the apex of the bow in the femur. Note the magnet inside the nail (green arrow) and the distraction rod, which is extended to 4 cm (red arrow). **B,** Lateral radiograph showing the straightening of the anterior bow of the femur.

Retrograde Femur

Indications

This technique is indicated for skeletally mature patients with arthrodesis or deformity of the hip or proximal femur that precludes the use of antegrade femoral nailing. Retrograde femoral nailing can be used in the setting of a distal deformity that will be corrected with osteotomy and for cases in which antegrade femoral lengthening will result in deviation of the mechanical axis.

Planning

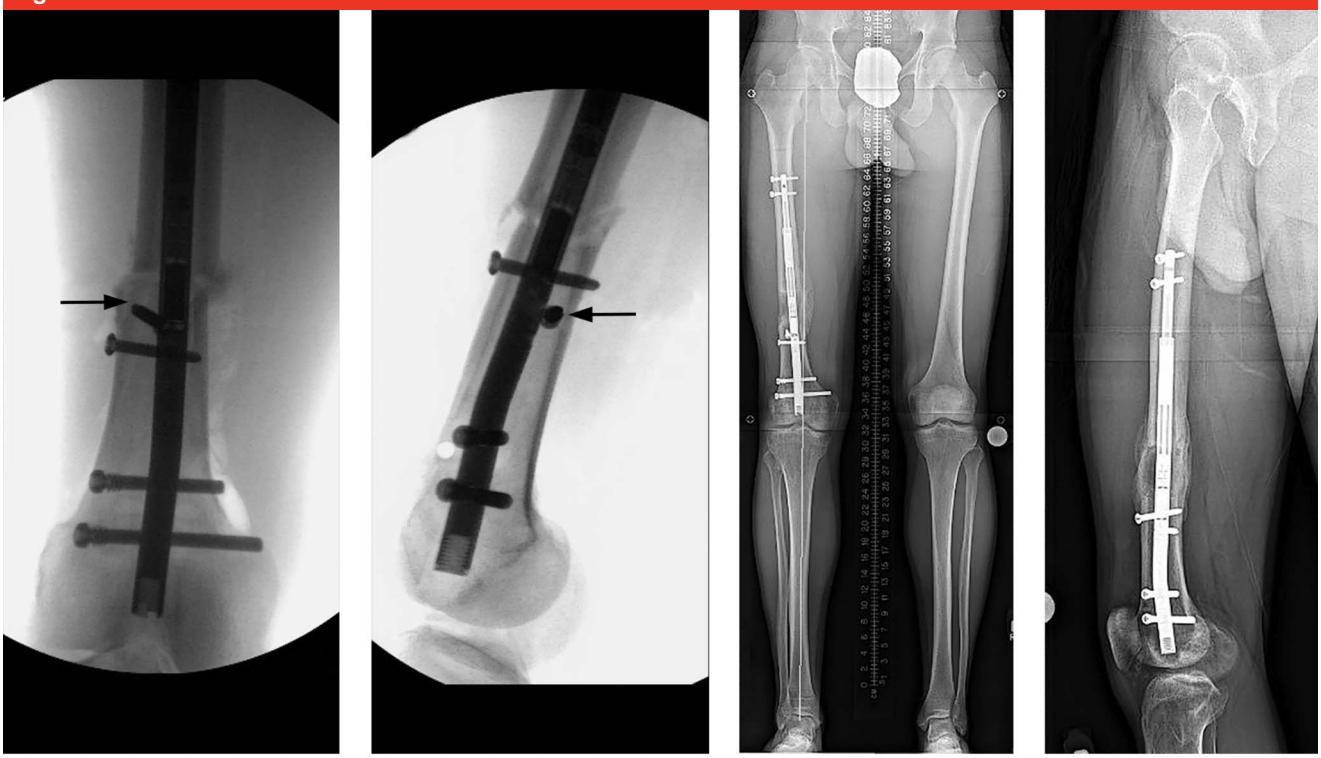
Preoperative planning is performed using the method described by Baumgart.[13] In this method, planning can be done with simple tracings of the preoperative full-length standing radiographs of the lower extremities or commercially available software systems. Alternatively, after the osteotomy is performed at the apex of the deformity, the bone can be straightened and held reduced with a temporary external fixator.[14]

Surgical Technique

A radiographic grid is placed under the patient, with the hip centered over the grid marker. The distal femoral joint line orientation, patella, and anatomic and mechanical femoral axes are marked on the skin. The osteotomy level, planned nail position, and junction of the telescopic portion of the nail are marked on the skin, with a skin clip used to guide reaming depth. The knee is flexed approximately 30° to 40°, and this position is supported with a sterile radiolucent triangle or bolster.

The femoral canal is vented through the osteotomy site by drilling multiple holes through a 1-cm lateral incision. Two Shanz pins, one above and the other below the osteotomy,

Figure 2



Intraoperative AP (**A**) and lateral (**B**) fluoroscopic images of the femur in a 29-year-old man with a preoperative limb-length discrepancy of 3.8 cm and valgus deformity of 5° secondary to posttraumatic growth arrest. **A,** A retrograde approach was used to correct the deformity, and a lateral blocking screw (arrow) was placed to prevent recurrence of valgus. **B,** A posterior blocking screw (arrow) was placed to prevent flexion during lengthening. Blocking screws were inserted because the intramedullary canal was larger than the diameter of the nail at the osteotomy site. Postoperative AP (**C**) standing radiograph of the lower extremities and lateral (**D**) radiograph of the femur made 5 months after surgery showing equal leg length and correction of deformity.

are placed parallel to each other in a lateral-to-medial direction. An infrapatellar incision is made, and a guidewire is inserted to a point of the intercondylar notch anterior to the origin of the anterior cruciate ligament. The wire is directed along the planned path for reaming of the distal bone segment. A sleeve is used to protect the soft tissues during reaming.

The osteotomy is performed using an osteotome at the venting site. The bone is angulated and translated to the preoperatively planned position. This may be held in position with a temporary external fixator. Blocking screws may be inserted at this point to guide the path of the reamer. The bone is reamed 2 mm greater than the diameter of the IM nail. The nail is then inserted with hand pressure, and alignment is checked on the radiographic grid. If necessary, adjustments in alignment are made at this point, and locking and blocking screws are inserted (Figure 2).

Tibia

Indications

Tibial lengthening with a telescopic nail is ideal for the skeletally mature patient with a 1.5- to 6-cm LLD, a straight bone with no deformity, an open medullary canal, and adequate bone size to accommodate an IM nail. In select patients, minimal deformity (eg, <10°) can be corrected acutely to allow passage of the telescopic nail provided that the apex of the deformity (level of the correction) is amenable for the stability of the fixation. This limits acute correction to the junction of the upper and middle third of the tibia and, sometimes, to the diaphysis. Corrections in the proximal third of the tibia may not be stable since the IM canal is much wider than the nail. Corrections in the distal half of the bone may not have adequate distal purchase at the end of lengthening since the thick part of the nail is pulled out of the distal fragment as the lengthening proceeds.

Deformity correction should be performed using fixator-assisted nailing

techniques,[14] and blocking screws should be inserted to maintain the correction. Alternatively, the lengthening procedure can be staged, with fixator-assisted nailing or plating initially performed to correct the deformity. After the osteotomy has healed, exchange nailing can be performed using a telescopic nail, with an osteotomy to lengthen the bone. Equinus deformity can be corrected by lengthening the triceps surae complex (eg, gastrocnemius-soleus complex recession, Achilles tendon lengthening).

Planning

The level of the tibial osteotomy and nail length are selected. The skin is marked at the level of the tibial osteotomy. The IM nail does not need to span the entire length of the tibia. Short nails that end at the mid shaft are less likely than long nails to get stuck during distraction, and 5 cm of the thick portion of the nail should remain in the distal segment of the bone at the end of the distraction phase.

Surgical Technique

The patient is positioned supine on a radiolucent table with the image intensifier on the opposite side of the surgical extremity. Perioperative antibiotic prophylaxis is required. The tourniquet is inflated after the limb is exsanguinated. A transverse or oblique osteotomy is performed at the junction of the middle and distal thirds of the fibula via the internervous plane between the peroneal and soleus muscles. A prophylactic anterior compartment fasciotomy is performed through a 2.5-cm incision. A gastrocnemius-soleus complex recession or Achilles tendon lengthening should be considered, particularly in the setting of tightness or lengthening >2 cm. A parapatellar or transpatellar tendon approach is used to access the proximal tibia. With guidance provided by the biplanar image intensifier, a Steinmann pin is inserted through the entry point into the tibial IM canal, followed by a cannulated reamer. The tourniquet should not be used beyond this point. A syndesmosis screw is needed to prevent disruption of the distal tibiafibula relationship at the ankle during lengthening. To insert a 4.5-mm diameter syndesmotic screw (solid core, fully threaded, cortical) into the distal tibia and fibula, a 1.8-mm Kirschner wire is drilled from the fibula (small target) to the tibia (large target). A lateral view of the tibia and fibula obtained with the image intensifier can be used to confirm whether the wire has captured both bones. A 3.2-mm cannulated drill bit is then used to drill a hole from medial to lateral in a retrograde direction. A screw is inserted from medial to lateral, with care taken to ensure purchase in all four cortices.

A 1-cm vertical incision is made, and a small periosteal elevator is used to raise the medial and lateral periosteum. Several drill holes are made at this level with a 3.2- or a 4.8-mm drill bit. This decompresses the canal, reducing the likelihood of fat embolism and permitting egress of reamings that then function as bone graft at the osteotomy site.

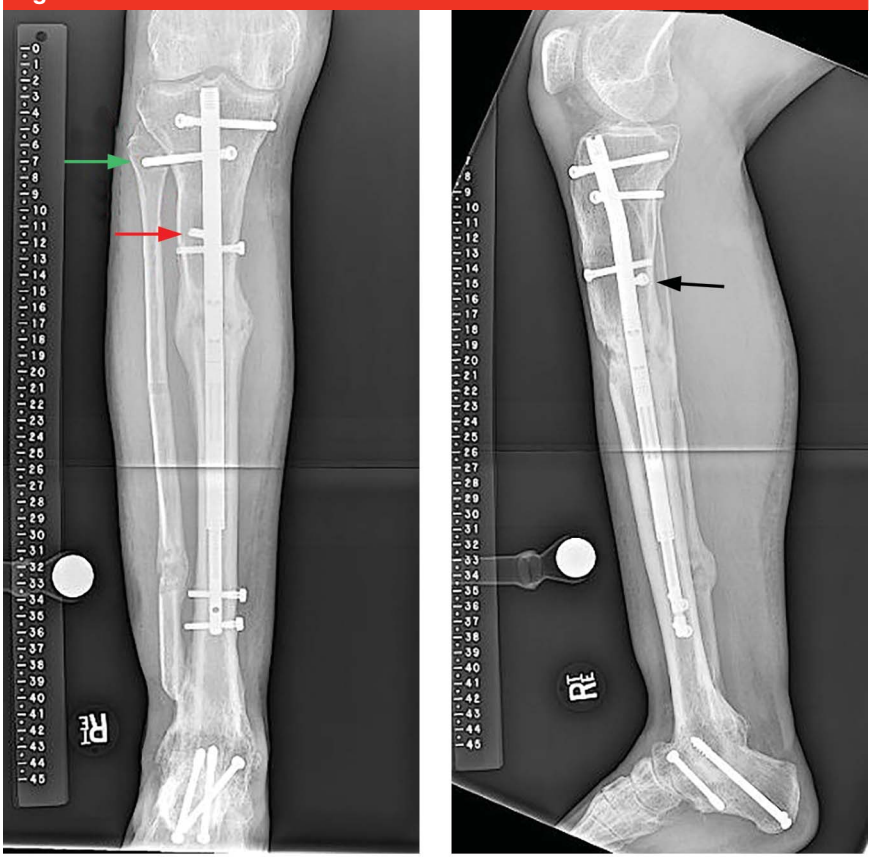
The knee is flexed maximally, and flexible reamers are used over a beaded guidewire to enlarge the tibial canal, increasing by increments of 0.5 mm until the canal is a full 2 mm larger than the outer diameter of the selected nail. The nail is assembled and tested with the jig to ensure the alignment of the proximal interlocking holes. The knee is extended and the osteotomy is completed with an osteotome. The bone is manually held in a reduced position while the knee is flexed and the nail is inserted past the osteotomy site and is fully seated. The proximal interlocking screws are inserted, the insertion jig is removed, and the knee is extended for insertion of the distal interlocking screws. Pins may be inserted outside the path of the nail to mark rotation before the osteotomy is performed. The thigh-foot axis is assessed to ensure that no inadvertent derotation has taken place. The distal interlocking screws are inserted using a freehand technique. The nail is tested by distracting 1 mm during surgery. Finally, a proximal tibiofibular syndesmotic screw is inserted from the equator of the head of the fibula directly transverse through both cortices of the tibia behind the path of the nail to prevent the descent of the fibular head during lengthening. An oblique proximal tibia locking screw can sometimes be used to capture the proximal fibula for this same purpose. This step may be omitted for lengthenings <2.5 cm. Blocking screws are inserted adjacent to the IM nail to prevent deformity if the diameter of the canal is larger than the nail at the osteotomy level (Figure 3).

Pearls and Pitfalls

To achieve optimal outcomes with the use of motorized IM nails for LLD and deformity, the orthopaedic surgeon must ensure that the bone is large enough to accommodate the reaming required for insertion of the IM nail (ie, 2 mm larger than the diameter of the nail). The osteotomy should be performed at the apex of the deformity or at the bow in the bone because the nail is straight. Propagation of the osteotomy should be avoided in order to maintain optimal stability. The nail should be advanced with minimal resistance to avoid damaging the distraction mechanism.

If the osteotomy is done at the isthmus, the use of blocking screws will not be required. However, if the width of the IM canal is larger than that of the nail at the osteotomy level, blocking screws can be inserted into

Figure 3



A B

A, Postoperative AP radiograph of the tibia obtained at the end of the distraction phase following a staged 4-cm lengthening procedure performed in a 33-year-old man. The patient had a limb-length discrepancy of 5 cm following ankle-subtalar fusion for a failed pilon fracture. Note the placement of the lateral blocking screw (red arrow), which prevents valgus deformity, and the screw inserted proximally through the tibia and fibula (green arrow) to prevent distal migration of the proximal fibula during lengthening. **B**, Lateral radiograph of the tibia showing the placement of the posterior blocking screw (arrow) that was inserted to prevent the development of procurvatum deformity.

the concavity of the anticipated deformity (eg, valgus-flexion deformity of the tibia, varus-flexion deformity of the femur) close to the osteotomy to prevent deformity during lengthening. To confirm completion of the osteotomy, the bone is rotated around the IM nail. Steinmann pins or temporary external fixation pins placed outside the nail tract are helpful to mark rotation, allowing the surgeon to prevent or correct rotational deformity. To ensure adequate stability of the fixation construct, 5 cm of the thick portion of the nail should remain in the moving segment at the end of distraction. As lengthening proceeds, the thick portion of the IM nail is pulled out of the moving segment. The length of the nail must be planned such that adequate stability is maintained at the end of distraction.

Postoperative Management

Patients are limited to touch-down weight bearing immediately after surgery. In adults, supplemental vitamin D and calcium are prescribed as well as a 2-week course of deep vein thrombosis prophylaxis. In adolescents, supplemental vitamin D and calcium are prescribed, but deep vein thrombosis prophylaxis is not routinely prescribed.

Physiotherapy is instituted for tibial lengthening, with a focus on ankle dorsiflexion and knee extension. The patient wears an ankle dorsiflexion split during the day and a knee extension brace at night. For femoral lengthening, physiotherapy focuses on knee flexion/extension and hip extension. In the femur, distraction is begun 4 to 6 days postoperatively at a rate of 0.33 mm three times daily or 0.25 mm four times daily. For tibial lengthening, distraction is begun 7 to 10 days postoperatively.[1,2] The distraction rate is 0.25 mm four times daily but may be decreased to two or three times per day during follow-up visits based on the radiographic appearance of new bone formation. Femoral bone formation during lengthening tends to be more robust than bone formation in the tibia. If bone formation is slow, the use of a bone-growth stimulator system can be considered. Follow-up visits take place every 1 to 2 weeks during the distraction phase and every 4 weeks during the consolidation phase.[1-3] Full weight bearing is allowed when corticalization of three of four cortices is seen on biplanar radiography. Once healing is complete, physiotherapy is modified to physical training. Typically, the telescopic implant is removed 1 year after surgery, provided there is solid circumferential healing of the regenerated bone.

Outcomes

Published reports on the Albizzia nails and ISKD suggest a generally

positive patient and physician experience.[10,11] However, patient refusal to rotate the limb, particularly with the Albizzia nail, and an inability to accurately control rate of distraction with the ISKD can cause significant complications.[15-17] Mechanical failure also has been reported with the use of both of these devices.[15-17]

Clinical case series on the Fitbone nail report favorable outcomes and patient satisfaction, with relatively few instances of mechanical failure of the implant or problems with distraction.[18,19] Early studies on the PRECICE nail have reported high rates of accuracy of distraction, maintenance of joint motion and bone alignment, and few complications.[19-21]

Summary

Mechanical integrity and accurate control of the rate and rhythm of distraction are critical to the success of limb lengthening with a motorized IM nail. Early designs for fully mechanical nails produced unreliable results and complications.[15-17] Modern motorized IM nail designs use a magnetic or electrical remote control to distract the bone, and early surgical outcomes have been promising. Although internal lengthening has obvious advantages over lengthening with an external fixator, appropriate patient selection is crucial. External fixation and hybrid techniques such as lengthening over an IM nail,[5,7,8,17] lengthening and then nailing,[3] and lengthening and then plating[4] will continue to be necessary for specific cases. However, the motorized IM nail is an important new tool for the management of LLD and deformity.

References

Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, references 3-5, and 17 are level III studies. References 6, 10-12, 15, 16, 18, 20, and 21 are level IV studies. References 1, 2, 7, 8, 13, and 14 are level V expert opinion. References printed in **bold type** are those published within the past 5 years.

1. Ilizarov GA: The tension-stress effect on the genesis and growth of tissues: Part I. The influence of stability of fixation and soft-tissue preservation. *Clin Orthop Relat Res* 1989;(238):249-281.
2. Ilizarov GA: The tension-stress effect on the genesis and growth of tissues: Part II. The influence of the rate and frequency of distraction. *Clin Orthop Relat Res* 1989;(239):263-285.
3. Rozbruch SR, Kleinman D, Fragomen AT, Ilizarov S: Limb lengthening and then insertion of an intramedullary nail: A case-matched comparison. *Clin Orthop Relat Res* 2008;466(12):2923-2932.
4. **Harbacheuski R, Fragomen AT, Rozbruch SR: Does lengthening and then plating (LAP) shorten duration of external fixation? *Clin Orthop Relat Res* 2012;470(6):1771-1781.**
5. Paley D, Herzenberg JE, Paremain G, Bhave A: Femoral lengthening over an intramedullary nail: A matched-case comparison with Ilizarov femoral lengthening. *J Bone Joint Surg Am* 1997;79(10):1464-1480.
6. Bost FC, Larsen LJ: Experiences with lengthening of the femur over an intramedullary rod. *J Bone Joint Surg Am* 1956;38(3):567-584.
7. Herzenberg JE, Paley D: Femoral lengthening over nails (LON). *Tech Orthop* 1997;12(4):240-249.
8. Herzenberg JE, Paley D: Tibial lengthening over nails (LON). *Tech Orthop* 1997;12(4):250-259.
9. Bliskunov AI: Intramedullary distraction of the femur (preliminary report) [Russian]. *Ortop Travmatol Protez* 1983;10(10):59-62.
10. Guichet JM, Deromedis B, Donnan LT, Peretti G, Lascombes P, Bado F: Gradual femoral lengthening with the Albizzia intramedullary nail. *J Bone Joint Surg Am* 2003;85(5):838-848.
11. Cole JD, Justin D, Kasparis T, DeVlught D, Knobloch C: The intramedullary skeletal kinetic distractor (ISKD): First clinical results of a new intramedullary nail for lengthening of the femur and tibia. *Injury* 2001;32(suppl 4):SD129-SD139.
12. Baumgart R, Betz A, Schweiberer L: A fully implantable motorized intramedullary nail for limb lengthening and bone transport. *Clin Orthop Relat Res* 1997;(343):135-143.
13. Baumgart R: The reverse planning method for lengthening of the lower limb using a straight intramedullary nail with or without deformity correction: A new method. *Oper Orthop Traumatol* 2009;21(2):221-233.
14. Paley D, Herzenberg JE, Bor N: Fixator-assisted nailing of femoral and tibial deformities. *Tech Orthop* 1997;12(4):260-275.
15. **Mazeau P, Assi C, Louahem D, L'Kaissi M, Delpont M, Cottalorda J: Complications of Albizzia femoral lengthening nail: An analysis of 36 cases. *J Pediatr Orthop B* 2012;21(5):394-399.**
16. **Burghardt RD, Herzenberg JE, Specht SC, Paley D: Mechanical failure of the Intramedullary Skeletal Kinetic Distractor in limb lengthening. *J Bone Joint Surg Br* 2011;93(5):639-643.**
17. **Mahboubian S, Seah M, Fragomen AT, Rozbruch SR: Femoral lengthening with lengthening over a nail has fewer complications than intramedullary skeletal kinetic distraction. *Clin Orthop Relat Res* 2012;470(4):1221-1231.**
18. Krieg AH, Speth BM, Foster BK: Leg lengthening with a motorized nail in adolescents: An alternative to external fixators? *Clin Orthop Relat Res* 2008;466(1):189-197.
19. Dahl MT, Birch JG: Motorized implantable lengthening nails for limb length discrepancy: 7 year North American experience. Presented at the 23rd Annual Scientific Meeting of the Limb Lengthening and Reconstruction Society, New York, NY, July 19-20, 2013.
20. Kirane Y, Fragomen AT, Rozbruch SR: Precision of the PRECICE internal bone lengthening nail. *Clin Orthop Rel Res* 2014; March 28 [Epub ahead of print].
21. Shabtai L, Specht SC, Standard SC, Herzenberg JE: Internal lengthening device for congenital femoral deficiency and fibular hemimelia. *Clin Orthop Rel Res* 2014; March 25 [Epub ahead of print].