

Motorized Internal Limb Lengthening: An Updated Review

Mark T. Dahl, MD^{1,2}; Andrew G. Georgiadis, MD^{1,2}; Stewart G. Morrison, MBBS^{1,3}

¹Gillette Children's Specialty Healthcare, St. Paul, MN; ²University of Minnesota, Minneapolis, MN; ³The Royal Children's Hospital Melbourne, Parkville, VIC, Australia

Abstract: Remotely controlled motorized limb lengthening nails were first developed by Baumgart and Betz in 1992. Two devices are now FDA approved in the United States: the FITBONE® (Orthofix® International, Curaçao, Netherlands Antilles) and the PRECICE® (NuVasive, San Diego, CA) nails, controlled by external signals (radiofrequency and magnetic, respectively). Motorized internal limb lengthening is now established as a safe and reliable technique, relying on sufficient training of the surgeon and education of the patient. This review discusses the most common pediatric applications for the lower limb, including patient indications, preoperative planning, surgical steps, pearls, and pitfalls.

Key Points:

- Motorized internal lengthening nails have been safely employed in adults and children.
- The surgeon should understand the principles of limb lengthening.
- The surgeon should understand the principles and techniques of intramedullary nailing.
- Skeletal maturity, predicted length discrepancy, and discrepancy etiology informs treatment strategy.
- Complications common to all limb lengthening methods, such as joint subluxation and poor regenerate formation, still exist and must be anticipated.

Introduction

Limb lengthening has evolved from early techniques involving open osteotomy distracted by traction¹ to Ilizarov's methodology of distraction osteogenesis with established scientific principles.^{2,3} A blood-supply preserving corticotomy, latency period, regular rate and rhythm of distraction, stable fixation, and functional limb use during treatment are the established tenets of limb lengthening surgery regardless of surgical technique. Although the Ilizarov method is based on biological and mechanical concepts, pin site complications and the discomfort of external fixation result in patient dissatisfaction during the process. This

review describes the advantages and limitations of motorized intramedullary limb lengthening (MILL) in pediatric patients.

History

Bliskunov described an internal lengthening device that consisted of an intramedullary femoral rod bolted to the iliac wing which lengthened via a ratchet mechanism.⁴ Cole introduced a device, the intramedullary skeletal kinetic distractor (ISKD) (Orthofix® International, Curaçao, Netherlands Antilles), that lengthened by limb rotation.⁵ The Guichet® nail, introduced in France by



Figure 1. The PRECICE® telescopic nail is activated by magnetic energy imparted by a hand-held controller.

Guichet, also utilized mechanical actuation.⁶ These devices require the patient to perform intermittent axial rotation of the limb to effect distraction, with resultant difficulty in controlling the lengthening rate.^{7,8}

The current technology of fully implantable, externally controlled motorized lengthening nails was introduced by Baumgart and Betz in 1992.⁹

Radiofrequency waves and a subcutaneous transceiver incite distraction via an actuator within the telescopic nail. Distraction only occurs when the transducer is placed directly over the receiver, allowing precise control of distraction rate and rhythm. FITBONE® devices (Orthofix® International, Curaçao, Netherlands Antilles) are available for antegrade or retrograde femoral lengthening, tibial lengthening, bone transport, and amputation stump lengthening. Additionally, Baumgart published “*The Reverse Planning Method*” in 2009,¹⁰ providing a practical tool for accurately managing both deformity as well as mitigating limb malalignment induced by lengthening along the anatomic, rather than mechanical, axis of the femur.

The PRECICE® nail (NuVasive®, San Diego, CA) was introduced in 2012, utilizing a magnetic drive mechanism, activated by a hand-held external controller (Figure 1). The patient or caregiver performs distraction by applying the surgeon-programmed controller directly over the internal magnet in the limb as instructed, with the latency, rate, and rhythm being adjusted by the surgeon based on weekly clinic visits and radiographs.

Indications and Preoperative Considerations

Pediatric limb length discrepancy may be due to congenital conditions like fibular hemimelia and

congenitally short femur, as well as acquired conditions including fracture malunion and traumatic or septic physeal arrest. Clinical and nonclinical factors that may influence a limb lengthening plan are summarized in Table 1.

When meeting a child with a limb length discrepancy for whom lengthening may be indicated, preparation includes devising a treatment plan for the patient’s entire childhood and adolescence, which may involve multiple staged lengthenings. Other treatment options may exist in combination and include external fixator lengthening, contralateral epiphysiodesis, shoe lifts, or even opposite limb shortening. A multidisciplinary team consisting of surgeon(s), inpatient and outpatient nurses, physical therapists, and orthotists is employed in most cases.

Pediatric patients suitable for MILL must have adequate canal diameter and bone segment length to accept available devices. Anatomic considerations unique to a pediatric population include the preservation of growing physes and the vulnerable blood supply to the immature femoral head. Children not amenable for MILL may be candidates for lengthening via other techniques, such as

Table 1.
Factors Contributing to Decision Making
when Evaluating Limb Length Discrepancy

Etiology
Magnitude of Discrepancy Now and at Maturity
Age and Anticipated Height at Maturity
Limb Segment Involved (Femur, Tibia, or Humerus)
Bone Deformity and Size
Adjacent Joint Stability and Motion
Neurovascular and Soft Tissue Status
Condition of the Foot
Medical Comorbidities
Family and Social Dynamics

external fixation or off-label use of newly available, extramedullary devices.

To date, deformity correction, if performed concomitantly, must be done acutely at the time of motorized nail placement. This is currently limited to mild deformities and preserves the role of external fixation in certain patients.¹¹ Iatrogenic deformities should be anticipated and avoided using appropriate preoperative planning.¹⁰

Preoperative Planning

Imaging

Preoperative studies prior to lower limb lengthening should include a standing radiograph of both lower extremities with the pelvis leveled by the placement of measured blocks under the shorter limb. Limb, segment, and joint alignment should be evaluated according to standard deformity analysis. Segment lengths should be measured to ascertain the source of the limb length discrepancy. A lateral X-ray of the bone intended for lengthening is necessary, quantifying any sagittal deformity and allowing assessment of canal diameter (Figure 2). A calibration disc may be used in order to assist with accurate measurement and planning. Digital or manual templates may then be carefully applied to radiographs, allowing specific anatomy to be considered (i.e., fit of an implant within the lengthened segment). For example, the nail length selected should allow 4-5cm of the widest diameter of the nail to be within the distracted segment at the completion of distraction.

Deformity and Alignment

If a deformity is identified, the apex should be located, and a decision made as to whether concomitant deformity correction is possible. Be aware of any pre-existing rotational deformity, best assessed by either clinical examination or axial imaging. Not all deformity may be corrected acutely, and the ideal site for deformity correction may not be the ideal site for lengthening corticotomy. Further details on choosing antegrade or retrograde technique will be discussed below.

MILL lengthens along the anatomic axis of the bone. In the femur, this creates medial translation of the knee and hence lateral translation of the mechanical axis. This translation is often approximated at 1 millimeter per centimeter of lengthening, but depends on the magnitude of deformity, location of corticotomy, size of the patient, and neck-shaft angle.¹²



Figure 2. Preoperative standing AP X-ray of both lower extremities with a block under the short limb to level the pelvis, in addition to a lateral XR to assess for sagittal plane deformity.

This is particularly important to anticipate in cases with a pre-existent genu valgum, often present in patients with congenital limb deficiencies or children who sustained premature distal femoral physeal arrest. Such cases may benefit from retrograde lengthening planned via Baumgart's Reverse Planning Method. This method provides a practical framework for achieving ideal alignment at the conclusion of lengthening, without the need for secondary osteotomy. Readers are strongly encouraged to comprehensively familiarize themselves with this planning technique.¹⁰

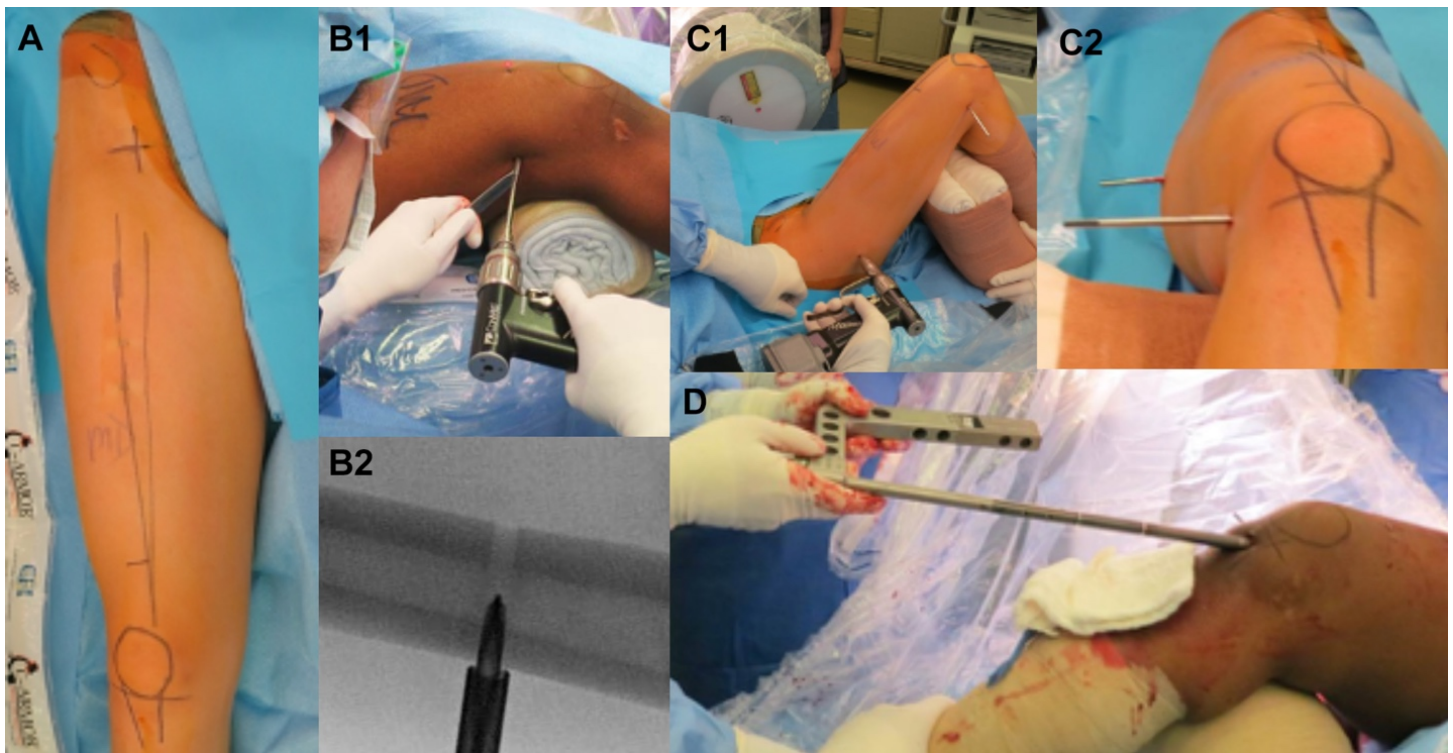


Figure 3. A. Skin markings act as visual aids and potentially decrease X-ray exposures. B. Initial corticotomy preparation acts additionally as a method for ‘venting’ the canal. C. Schanz pins offer a temporary external fixator for maintaining rotational alignment and manipulating bone segments. D. Nail insertion is performed by hand pressure; mallet is avoided as it may damage the internal lengthening mechanism.

Operative Technique

Visual Aids

The authors routinely use scaled preoperative images and templates displayed in the operating theatre for ongoing reference. The hip, knee, and ankle joint centers, patella, and axes of each long bone should be marked on the overlying skin with a sterile marking pen using fluoroscopic guidance. This assists with orientation of the limb intraoperatively. The level of the proposed corticotomy should then be marked. Systematically establishing these visual aids at the onset of every case may reduce later fluoroscopic burden. A radiographic grid is placed under the patient, and the hip position is centered over the grid marker. The orientation of the distal joint line, patella, and the anatomic and mechanical tibial and femoral axes are marked with sterile skin markers (Figure 3A). The corticotomy level, future nail position, and junction of the telescopic

portion of the nail are marked with skin clips to guide reaming depth and direction.

Venting the Canal

It is accepted practice to ‘vent’ the canal at the location of the planned corticotomy in order to mitigate the risk of fat embolism due to elevated intramedullary pressure during reaming (Figure 3B). The corticotomy site is approached through a small skin incision, followed by a percutaneous longitudinal incision and elevation of the periosteum. The bone is drilled using a 4-5mm drill bit to place up to eight holes. A new drill bit should be used for each case, and cleaned between passes, minimizing friction and the risk of thermal necrosis. Periosteal damage is minimized by minimal drill bit ‘plunging’ and the use of a protective sleeve. The added advantage of early corticotomy preparation is the spilling of reamings into the corticotomy site, potentially adding biological support to the lengthening site.

Schanz Pins

Placement of temporary Schanz pins may assist as a visual aid for the maintenance of rotational alignment, or to achieve an angular/rotational correction by attachment of temporary external fixation (Figure 3C). Pins must be placed so as to avoid interference with nail insertion. In the distal femur, a 'perfect' lateral fluoroscopic image should be obtained, and the pin placed posteriorly, parallel to the joint line. A proximal femoral pin is inserted above the limit of the future nail (if using a retrograde method), or posteriorly enough to allow nail passage (if antegrade). Similar guidance applies if Schanz pins are to be used in the tibia. Pins should align axially or recreate the planned rotational correction (if applicable) such that they are axially aligned at the conclusion of correction.

Nail Entry Point

Ideal entry points are required for proper intramedullary nailing and have been defined (Figure 4). Trochanteric entry is on the medial tip of the trochanter without entering the piriformis fossa, and central on the trochanter on the lateral projection. Piriformis entry is aligned in both projections, with the AP view showing the starting point slightly below the base of the neck and the lateral view centered on the diaphysis, not the trochanter. In order to prevent AVN, piriformis nailing should only be considered for patients who are skeletally mature. Tibial entry is slightly lateral to knee center (on the medial aspect of the lateral spine) on the AP projection and slightly posterior to the anterior cortical margin on the lateral view. Too anterior an entry will result in procurvatum deformity and too lateral an entry



Figure 4. From left to right, A. Trochanteric entry is at the medial most tip of the trochanter. Entering the trochanter too lateral results in varus deformity. B. Piriformis entry is at the depth of the piriformis fossa slightly posterior of center on the lateral view, yet in alignment with the canal on both views. C. Retrograde femoral entry is just posterior to the hyaline cartilage of the sulcus and anterior to the posterior cruciate ligament. D. Tibial entry is slightly lateral to knee center on the AP view and slightly posterior to the anterior cortical margin on the lateral view. Too anterior an entry will result in procurvatum deformity and too lateral an entry will result in valgus deformity.

will result in valgus deformity. If available, retrograde femoral nailing should be performed with reaming sleeves to protect the hyaline cartilage from reamer blades and the joint itself from reaming spillage.

Reaming Techniques

Reaming should proceed carefully, without haste, with attention to maintenance of entry point. Excessive force may encourage undesirable eccentric reaming even if a guidewire is used.

Flexible Reaming

This technique is used in most antegrade femoral and tibial applications. The canal is first vented by placing percutaneous drill holes the site of the planned corticotomy. A ball-tipped guidewire is placed. Flexible reamers are slowly passed in 0.5mm increments. As telescopic nails are straight and the canal is not, the use of flexible reamers necessitates the over-reaming of the canal by 1-2mm, to allow for passage of a straight nail into a curved path.

Rigid Reaming

This is most useful in retrograde femoral applications where accurate control of correction is required. A 3mm guidewire is inserted in the proper entry point, at the appropriate angle in both planes as planned preoperatively to result in the planned correction. For example, a 15-degree distal femoral flexion deformity requires an insertion angle 15 degrees anterior to the anatomic axis. The guide wire position in the frontal plane must exactly match the preoperative planning to result in a normal lateral distal femoral angle and a centered mechanical axis at completion of lengthening. Reaming tubes assist with the maintenance of the planned reaming path. After canal preparation on the near (distal) side of the corticotomy, the corticotomy is completed with an osteotome. Planned correction is then carefully achieved, and rigid reaming proceeds to the far (proximal) segment. When using rigid reamers, over-reaming by as little as 0.5mm may be sufficient, affording additional intrinsic stability to the construct by creating a tighter fit.

Nail Insertion

Regardless of reaming technique, the nail is inserted by hand pressure (Figure 3D). If necessary, another pass with a larger diameter reamer should be chosen to prevent damage to the lengthening mechanism, which can occur during mallet-assisted insertion. Appropriate alignment is confirmed, the corticotomy is compressed by an axial load applied to the limb, and interlocking screws are inserted.



Figure 5. Blocking screws used to control alignment when nail:canal diameter mismatch exists.

Blocking Screws

Blocking (Poller) screws are useful in applications of intramedullary fixation for correcting and preventing deformity (Figure 5)^{13, 14}. They function to increase nail stability in epiphyseal and metaphyseal areas, or anywhere that cortical canal fit is not achieved. They can be placed before reaming or after nail placement. Their role in MILL is twofold: (i) guide reaming or nail insertion and (ii) to prevent deformity during lengthening, typically valgus-procurvatum during tibial lengthening and varus-procurvatum during femoral lengthening. Locking bolts may be threaded only at the near cortex for increased strength when used as interlocking screws (larger barrel diameter), but also allow nail translation along the smooth barrel of the bolt during the lengthening process.

Specific Techniques

Antegrade Femoral Lengthening

Patient Indications

Antegrade femoral lengthening is indicated for patients with leg length discrepancy originating predominantly from the femur (Figure 6). Mild angular and rotational deformity of the proximal to mid femur may be corrected. A piriformis entry point can be used for adults, and trochanteric entry has been shown to be safe for the femoral head blood supply in preadolescents as young as 12 years (15). Assessment of alignment, and specifically the weight-bearing line on preoperative X-rays should be performed as discussed previously, in order to avoid lateralization of the weight-bearing line leading to overload of the lateral compartment of the knee.



Figure 6. Example of antegrade, trochanteric-entry lengthening of the femur.

Antegrade Femoral Technique

MILL via antegrade technique may be performed on a radiolucent table either in the lateral position or supine with an appropriate bolster under the ipsilateral buttock. The supine technique will be described here. Following corticotomy preparation, the hip is adducted, skin

incised at the appropriate level, and a wire is inserted into the intramedullary canal at the predetermined entry point. A soft-tissue protector is used to protect gluteal musculature. The intramedullary canal is opened with a cannulated drill, and then reaming is performed by either the flexible or rigid method previously described. The assembled nail is inserted just short of the corticotomy site. An osteotome is used to complete the corticotomy, confirmed by fluoroscopy. The nail is passed across the corticotomy site. Proximal interlocking screws are inserted with the targeting jig. The corticotomy is manually compressed longitudinally. Distal locking screws are inserted. Iliotibial band release is performed for lengthening of greater than 3cm and in cases of congenital etiology.

Retrograde Femoral Lengthening

Patient Indications

Retrograde femoral lengthening is indicated for patients with any of the following:

- Where antegrade femoral lengthening will result in excessive mechanical axis deviation
- Deformity of the proximal femur preventing antegrade femoral nailing
- Distal femoral deformity suitable for concurrent correction
- Skeletally immature patients with complete distal femoral growth arrest

Retrograde femoral lengthening may be planned using the “The Reverse Planning Method” as discussed above (Figure 7).¹⁰

Surgical Technique

The femoral canal is vented through the future corticotomy site by drilling multiple holes (Figure 3B). Two Schanz pins are placed (Figure 3C) distal and proximal to the corticotomy site, in a lateral to medial direction to guide transverse plane alignment.



Figure 7. Retrograde lengthening, demonstrating use of the “Reverse Planning Method” with planned intraoperative alignment goal and blocking screw.

The infrapatellar ligament is split longitudinally through a 10mm infrapatellar incision, and a 3mm guidewire is inserted to a point in the intercondylar notch anterior to the PCL origin, and directed along the path that will allow for reaming of the distal bone segment as planned.

Biplanar fluoroscopic guidance for determining the exact entry point avoids hyaline cartilage injury. The articular surfaces are protected from reamers and reamings with a protective sleeve during insertion, removal, and exchange of reamers.

Reaming to the corticotomy level is performed in 0.5mm increments. The corticotomy is then completed with an osteotome. The osteotomy site is then angulated, translated, and/or rotated to the preoperatively planned position and held there by a femoral distractor or an assistant. Reaming of the diaphysis is performed to 0.5mm greater than the size of the nail. The nail is inserted with hand pressure and alignment is checked with the grid. Additional reaming is performed if the nail does not pass easily. Adjustments in alignment are made if needed and locking and blocking screws are added.

Tibial Lengthening

Patient Indications

Candidates for tibial lengthening using MILL should have a closed proximal tibial physis. Regenerate produced during tibial lengthening is often poorer than that seen in the femur, hence making single lengthenings of > 6cm unrealistic. While concurrent deformity correction may be performed, careful consideration must be given to the magnitude of acute correction and risk of neurovascular compromise or compartment syndrome. Certain deformities, particularly valgus deformity of the proximal tibia, are still more amenable to gradual correction with external fixation. Pre-emptive anterior compartment fasciotomy may be considered in more complex tibial cases.

Planning

Tibial anatomic and mechanical axes are collinear in a normal tibia and lengthening via MILL occurs along this shared axis. A modest tibial deformity may be acutely corrected to allow passage of a telescopic nail, provided that the apex of the deformity is amenable to stable fixation, and the surrounding neurovascular structures can safely tolerate the acute correction. Blocking screws are inserted during canal preparation for corrections in the proximal third of the tibia since valgus and procurvatum deformity routinely develops during lengthening. Distal tibial correction occurs where the canal is capacious and often requires enhanced fixation with additional blocking screws. These features limit acute corrections to the region of the junction of the upper and middle thirds of the tibia.

Surgical Technique

A fibular osteotomy is performed at the junction of the middle and distal thirds through the internervous plane between peroneal and soleus muscles. A 4.5mm fully threaded cortical screw is inserted from the fibula to the tibia with the foot in neutral to slight dorsiflexion. Proximal tibio-fibular screw transfixion can be accomplished in selected cases using the Rancho technique.¹⁶

An infrapatellar incision is used, and a medial parapatellar or tendon-splitting approach may be used. The starting point is achieved in the anterior intra-articular area under biplanar image intensifier control on the medial aspect of the lateral spine.

Corticotomy level is chosen at the deformity apex or ~8cm from the proximal joint line, allowing room for locking and blocking screws. Nail length is planned such that there will be 5cm of the wider portion of the nail in the distal segment after distraction is complete⁽¹⁷⁾. The corticotomy is performed through a 2-3cm vertical incision, with a tiny elevator lifting the medial and lateral periosteum. Multiple 5mm drill holes will vent the canal.

Schanz pins are placed for rotational control, yet parallel to the adjacent joints in the coronal plane. If utilizing a tourniquet, it must be deflated before entering the canal and reaming. Reaming proceeds in 0.5mm increments with either rigid or flexible reamers, with soft tissue protection and a flexed knee supported on a padded triangle. Posterior and medial blocking screws are routinely placed, mitigating valgus and procurvatum deformity.

The corticotomy is completed with an osteotome, the knee is flexed, and the nail inserted by hand pressure. The proximal interlocking jig will require removal to confirm alignment, as the knee will not fully straighten with the jig in place. When satisfied with alignment, insert the proximal interlocking bolts first. Manually compress the corticotomy. "Perfect circle" free-hand insertion of the distal interlocks is then completed.

Deformity correction can be achieved with the previously placed tibial Schanz pins, with each pin oriented parallel to the adjacent joint. Fixator assisted nailing techniques can also be used¹². Blocking screws should be used to prevent intraoperative deformity and prevent deformity from developing during lengthening.

An anterior compartment fasciotomy should be performed in patients at risk, such as those with

deformity corrections, previous compromise, or those anticipating greater lengthening goals (> 3cm). Gastrocnemius and soleus recession may be considered for longer lengthenings or those of congenital etiology. Further protection against equinus can be achieved by static or dynamic dorsiflexion bracing or extra-articular pinning, as described by Herzenberg¹⁷. Static pinning may result in stiffness, so screws should be removed promptly after length has been achieved.

Intraoperative Nail Testing for All Lengthenings

It is recommended to perform an intraoperative test lengthening of the nail to confirm mechanical function prior to closure. Each device has a different means of confirming implant distraction. Device-specific recommendations should be obtained by the manufacturer because it is difficult to assess a 1mm distraction of a drill corticotomy either by gross inspection or radiographic evaluation at the corticotomy site.

All nails are tested intraoperatively, before closure, to ensure mechanical function and that subsequent separation will occur postoperatively. The rate controller is set for maximum daily distraction and maximum total distraction. It is then brought into the sterile field after an X-ray is taken, showing both the corticotomy, magnet, and gearboxes. One millimeter of distraction is applied, and the X-ray repeated to demonstrate separation, best seen adjacent to the gearboxes. A tibial lengthening should then be reversed 1mm after the testing.

Postoperative Management

A lengthening plan should be formulated postoperatively. The 'latency period' prior to the commencement of lengthening should consider patient factors (age and comorbidities), bone factors (location within the bone, previous surgery and factors affecting vascularity, and typically a longer latency for the tibia when compared to the femur), and corticotomy factors (longer latency in the cases of larger acute corrections,

or disruption to the periosteum at the corticotomy site). Generally, the latency period will be 5-7 days or 7-10 days for a pediatric femur or tibia, respectively. Rotational and translational corrections may require an additional 2-5 days of latency.

A lengthening rate of 0.75mm-1mm per day is often achievable in pediatric patients but should be initially based on factors mentioned above and subsequently adjusted dependent on the (i) sequential radiographs examining regenerate density, volume, contour, and consistency, and (ii) the response of the patient's limb (pain, contracture). Lengthening should be divided into as few increments as practical. While often divided into four lengthening sessions per day, it is the senior author's opinion that smaller, more regular increments (e.g., eight times per day) may produce better regenerate formation. A fracture boot may support the foot and ankle in a neutral position in tibial lengthenings, and a knee immobilizer (at rest) may support the knee in extension during femoral lengthenings, during the lengthening phase.

Lengthening Phase

Weight-bearing should be restricted consistent with each manufacturer's recommendations and considering patient bone quality, fixation, and mobility factors. In general, weight-bearing is restricted to a maximum of 30 pounds until the consolidation phase and three cortices of bridging bone are present on X-ray.

Isometric exercises and active range of motion of adjacent joints are encouraged throughout the lengthening process. Weekly postoperative physical therapy visits are advised for contracture prevention, to which patients with congenital limb discrepancies are particularly susceptible. Therapy should prioritize ankle dorsiflexion and knee extension for tibial lengthenings, and knee and hip extension for femoral lengthenings.

Multimodal pain management utilizing acetaminophen and judicious use of oral opiates is advised. Pain results from the lengthening process, and hence, patients

potentially suffer pain over longer periods than is experienced after acute corrective surgery. Consider 2-6 weeks of thromboembolism prophylaxis appropriate to the patient's risk factors and local institutional policies.

Consolidation Phase

The weekly follow-up visits during the lengthening phase can be extended to monthly visits during the consolidation phase. Patients must be informed to prevent contracture, improve motion, and not exceed the 30-pound weight-bearing restriction during this phase. Full weight-bearing is not allowed until corticalization is radiographically evident on three of the four cortices seen on the AP and Lateral radiographs at the distraction site. Physical therapy can begin with strength and endurance training at this point. Removal of the implant is often performed one year after surgery, provided the regenerate bone is circumferentially corticalized.

Outcomes

The early experience with MILL nails report positive outcomes and patient satisfaction, and implant complications are few.¹⁸⁻²⁰ Examples of results achieved are shown in Figures 6 and 7. Accurate distraction, maintenance of joint motion and alignment, and lower complication rates have been noted compared with lengthenings by external fixation.²¹ Patients report significantly lower levels of pain in MILL, compared with external fixators.²² Reports of mechanical device failure, failure to distract, and nail breakage of the FITBONE® and PRECICE® are rare.^{23, 24}

Complications

Limb lengthening complications such as joint contracture, stiffness, subluxation, fracture, residual deformity, and chronic pain are well described and can still occur with MILL.²⁵ Lee²⁶ delineates complications of MILL which are 'device related' from those which are not, which allows recognition that while some complications are device-specific to external fixation, or MILL, many are common to any technique of limb lengthening surgery. While a comprehensive discussion

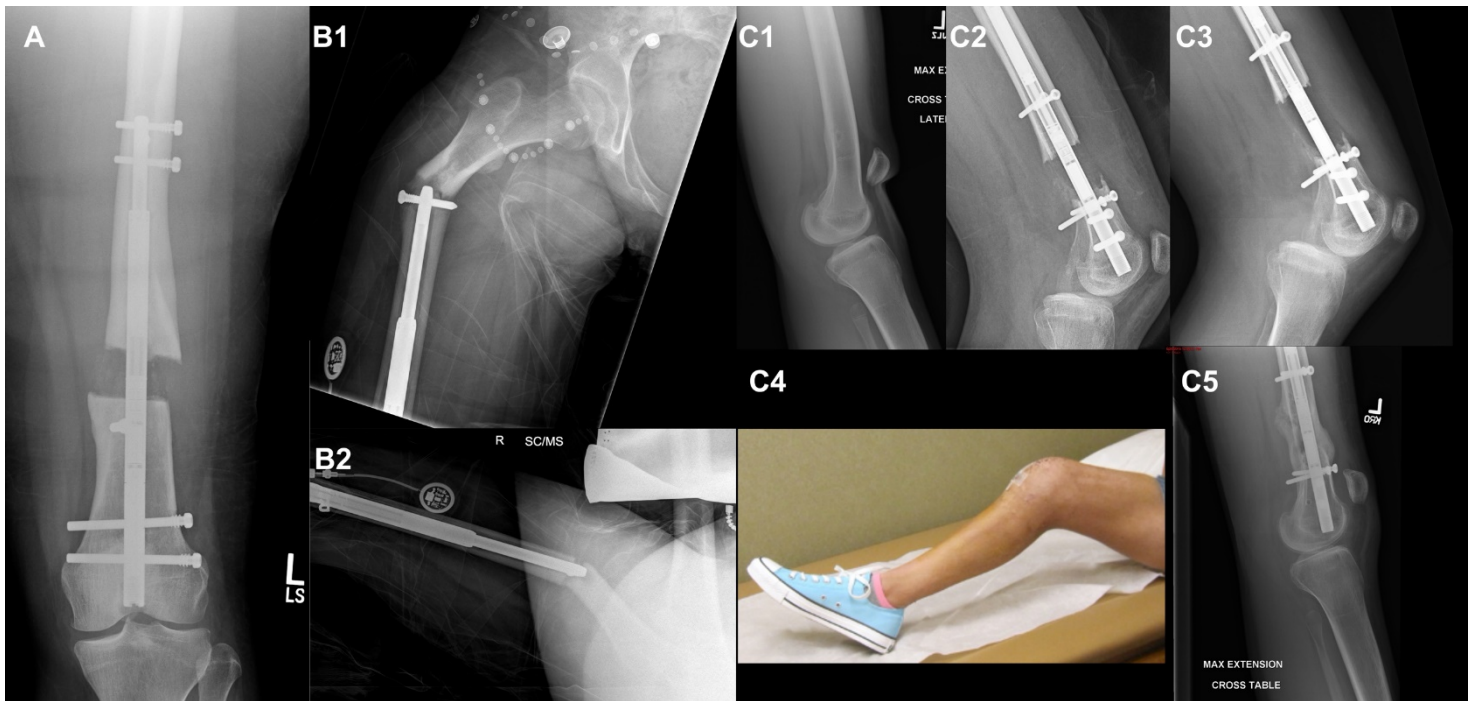


Figure 8. Complications: A. Insufficient regenerate formation in a retrograde femoral lengthening; B. Fracture at nail tip due to excessive reaming in the situation of a typically increased femoral procurvatum; and C. The typical cascade of knee joint contracture follows by subluxation, clinical photograph demonstrating typical ‘sag’ of proximal tibia. Salvage via reversal of lengthening and dynamic splinting.

of MILL complications and their mitigation and management is beyond the scope of this article, aspects of those most significant complications relevant to the pediatric population will be discussed here.

Premature consolidation describes the situation in which regenerate strength overcomes the power of the device to continue further distraction. Because of their propensity to make bone, pediatric patients are at higher risk of premature consolidation during lengthening when compared to adults. At each review, the lengthening site should be radiographically measured to ensure correlation with the lengthening program prescribed. If emerging premature consolidation is suspected, an accelerated schedule of 1.5 mm/day for 5 days, or even 1 mm in a single sitting under supervision in clinic, may prevent the need for repeat corticotomy around an *in situ* nail.

Poor regenerate formation should be corrected by stopping lengthening for 3-7 days, and then resuming the

lengthening at a slower rate until regenerate improves (Figure 8A). Particular vigilance should be given to situations of a previously multiply operated bone, or where acute correction has also been performed.

Fractures, either peri-device or of the device itself, can occur. Excessive reaming or attempted implantation of a nail that is simply too large for the patient may contribute. In situations of considerable femoral procurvatum, the tip of the nail abutting the anterior cortex may produce a stress-riser (Figure 8B). Smaller diameter nails often indicated in a pediatric population may bend or break in situations of poor regenerate formation or poor patient compliance. A ‘bending’ nail observed on X-ray warrants further weight-bearing restriction, or consideration of exchange to a trauma nail or plate.

Joint subluxation is the most catastrophic complication of limb lengthening, and once established, is seldom resolved to a satisfactory solution. Careful consideration

should be given to joint stability in patients with congenital etiology. Hip coverage should be assessed radiographically, and knee stability assessed for antero-posterior as well as rotatory instability. At risk joints may warrant prior surgical stabilization or spanning during lengthening with either internal or external fixation. Knee joint contracture follows a classic cascade of flexion contracture, translation, and posterior subluxation (Figure 8C). Physical therapy augmented by joint-specific static and dynamic bracing are of value.²⁷ If subluxation is suspected, lengthening must be stopped immediately, with consideration of reversal of lengthening if possible. A smaller magnitude of lengthening, with a plan to “return to fight another day,” is far better than 2-3cm of length gained at the expense of joint subluxation.

General Guidelines Summary

- MILL provides an alternative to external fixation. However, appropriate respect for active physes, pediatric femoral head blood supply, and overall bone and canal size is critical to success.
- Meticulous planning using calibrated, orthogonal radiographs allows accurate prediction of post-lengthening alignment and construct stability.
- Visual aids during surgery such as skin marking with a surgical pen, and Schanz pins to reference rotation or deformity correction, act as useful adjuncts that may not only improve results but also reduce radiation exposure.
- The canal should be vented at the site of the future corticotomy, prior to reaming.
- A corticotomy site may be used for deformity correction in select cases.
- Over-reaming requirements depend on the type of reamers used (1.5-2mm for flexible reamers, as low as 0.5mm for rigid reamers).
- Nails should be implanted by hand pressure only without the use of a mallet.

- Blocking screws prevent deformity, including deformity that may develop during lengthening. They are most commonly needed in areas of large canal-to-nail size ratio such as the distal femur and proximal tibia.
- The lengthening plan (latency, rate, rhythm) should be re-evaluated at weekly intervals during lengthening, and the patient reviewed monthly during the consolidation phase.
- MILL does not eliminate many of the complications intrinsic to the practice of limb lengthening.

Summary

Critical to the success of a motorized internal lengthening nail are combining proper surgical training, accurate preoperative planning, minimally invasive surgery, mechanical integrity of the construct, and ideal control of the latency, rate and rhythm of distraction. Early designs that were mechanically actuated had problems with rate control, resulting in bone formation complications. The two current designs use either magnetic or electrical control and have reliable use while eliminating pin and wire complications and fixator-associated pain. While internal lengthening has obvious advantages, complications associated with lengthening remain, and there are specific patient indications. Children with open growth plates or small bones are not suitable candidates. The motorized intramedullary lengthening nail is an important new tool for the limb length and deformity correction surgeon.

Additional Links

Green, S.A., Dahl, M.T., Intramedullary Limb Lengthening: Principals and Practice.

<https://www.springer.com/gp/book/9783319602967>

Rosbruch S.R., Birch J.G., Dahl M.T., Herzenberg J.E., Motorized intramedullary nail for management of limb-length discrepancy and deformity.

<https://www.ncbi.nlm.nih.gov/pubmed/24966246>

References

1. Codivilla A. On the means of lengthening, in the lower limbs, the muscles and tissues which are shortened through deformity. 1904. Clin Orthop Relat Res. 1994(301):4-9.
2. 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):249-81.
3. 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):263-85.
4. Bliskunov AI. [Intramedullary distraction of the femur (preliminary report)]. Ortop Travmatol Protez. 1983(10):59-62.
5. 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:SD129-39.
6. 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):838-48.
7. 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):394-9.
8. 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):639-43.
9. Baumgart R, Betz A, Schweiberer L. A fully implantable motorized intramedullary nail for limb lengthening and bone transport. Clin Orthop Relat Res. 1997(343):135-43.
10. 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. Operative Orthopadie und Traumatologie. 2009;21(2):221-33.
11. Burghardt RD, Paley D, Specht SC, Herzenberg JE. The effect on mechanical axis deviation of femoral lengthening with an intramedullary telescopic nail. J Bone Joint Surg Br. 2012;94(9):1241-5.
12. Paley D, Herzenberg J, Bor N. Fixator-assisted nailing of femoral and tibial deformities. Tech Orthop. 1997;12(4):260-75.
13. Ricci WM, O'Boyle M, Borrelli J, Bellabarba C, Sanders R. Fractures of the proximal third of the tibial shaft treated with intramedullary nails and blocking screws. J Orthop Trauma. 2001;15(4):264-70.
14. Krettek C, Stephan C, Schandelmaier P, Richter M, Pape HC, Miclau T. The use of Poller screws as blocking screws in stabilising tibial fractures treated with small diameter intramedullary nails. J Bone Joint Surg Br. 1999;81(6):963-8.
15. Gordon JE, Goldfarb CA, Luhmann SJ, Lyons D, Schoenecker PL. Femoral lengthening over a humeral intramedullary nail in preadolescent children. J Bone Joint Surg Am. 2002;84-a(6):930-7.
16. Green SA. The Ilizarov method: Rancho technique. Orthop Clin North Am. 1991;22(4):677-88.
17. Belthur MV, Paley D, Jindal G, Burghardt RD, Specht SC, Herzenberg JE. Tibial lengthening: extraarticular calcaneotibial screw to prevent ankle equinus. Clin Orthop Relat Res. 2008;466(12):3003-10.
18. Dahl M, Birch J, editors. Motorized implantable lengthening nails for limb length discrepancy: 7 year North American experience. Limb Lengthening and Reconstruction Society Annual Meeting; 2013; New York, NY.

19. Kirane Y, Fragomen A, Rozbruch S, editors. Precision of Internal Lengthening Nail. Limb Lengthening and Reconstruction Society Annual Meeting; 2013; New York, NY.
20. Herzenberg J, Standard S, Conway J, editors. Limb lengthening with a new controllable internal device in patients with congenital shortening. Limb Lengthening and Reconstruction Society Annual Meeting; 2013; New York, NY.
21. 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):189-97.
22. Herzenberg J, editor Standard patient reported pain levels. Limb Lengthening and Reconstruction Society Annual Meeting; 2013; New York, NY.
23. Baumgart R, Thaller P, Hinterwimmer S, Krammer M, Hierl T, Mutschler W. A Fully Implantable, Programmable Distraction Nail (Fitbone) — New Perspectives for Corrective and Reconstructive Limb Surgery In: Leung KS et al (eds) Practice of Intramedullary Locked Nails. Berlin: Springer; 2006.
24. Calder PR, McKay JE, Timms AJ, Roskrow T, Fugazzotto S, Edel P, et al. Femoral lengthening using the Precice intramedullary limb-lengthening system: outcome comparison following antegrade and retrograde nails. Bone Joint J. 2019;101-B(9):1168-76.
25. Dahl MT, Gulli B, Berg T. Complications of limb lengthening. A learning curve. Clin Orthop Relat Res. 1994(301):10-8.
26. Lee DH, Kim S, Lee JW, Park H, Kim TY, Kim HW. A Comparison of the Device-Related Complications of Intramedullary Lengthening Nails Using a New Classification System. Biomed Res Int. 2017;2017:8032510.
27. Green SA. Postoperative management during limb lengthening. Orthop Clin North Am. 1991;22(4):723-34.