Principles of Motorized Internal Lengthening of Long Bones

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Summary: Motorized intramedullary lengthening nails (ILNs) have revolutionized limb lengthening surgery and led to an expansion of indications utilizing them for both upper and lower limb lengthening, fracture compression, and nonunion treatment. There are biological and mechanical differences between using ILNs and using external fixators for lengthening surgery that the treating surgeon must be familiar with. Biological factors include regenerate quality, healing indices, and regenerate complications. Mechanical differences pertain to the lengthening axis, stability, and postoperative weight-bearing. Practical principles of ILNs use such as nail selection (entry point, nail length, lengthening nail problems), use of blocking screws, soft tissue releases (for nerve decompression, joint subluxation, and contractures) and physical therapy protocols are discussed.

Key Words: limb lengthening—intramedullary lengthening nail—lengthening nail—PRECICE nail—short stature.

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The advent of motorized intramedullary lengthening nails (ILNs) has been revolutionary in sparing patients the morbidity of external fixators.[1] Motorized ILNs have been successfully utilized in the treatment of lower extremity limb length discrepancy (LLD), upper extremity lengthening, compression of fractures, and nonunions.[2] The most common motor driven ILN's to date are the PRECICE nail (Nuvasive, San Diego, CA), and FitBone (Wittenstein, Igersheim, Germany). The PRECICE nail is a titanium telescopic magnet-driven implant that lengthens via an external remote controller (ERC). The ERC contains 2 rotating magnets that are placed over the nail's magnet and cause it to rotate, driving the gearbox and lengthening the nail. The PRECICE STRYDE nail (Nuvasive) is a newer version of the PRECICE nail composed of stainless steel that permits earlier weight-bearing. The FitBone nail is an electrically driven nail that lengthens via a gear and spindle mechanism. The electric energy delivery is via an external transmitter through the skin to a subcutaneous antenna, which connects to the spindle mechanism.[3] The authors experience is mainly with the PRECICE nail, and hence the discussion will focus on it.

The Law of Tension Stress was described by Gavril Ilizarov as "the gradual traction on living tissues creates stresses that can stimulate and maintain the regeneration of active growth of certain tissues."[4] This law led to the description of distraction osteogenesis, which is the formation of new bone in a widening distraction gap. This is the principle through which all surgical limb lengthening occurs regardless of implant utilized. Distraction osteogenesis undergoes 4 phases. Phase 1 is performing a low energy osteotomy. We typically perform a subperiosteal low energy osteotomy with designated 8 to 10 mm osteotomes (Fig. 1). Another option is to use a Gigli saw. Phase 2 is the latency phase in which the osteotomy site is left undistracted for a period of time, which is typically 5 to 7 days for the femur and 10 to 14 days for the tibia as it takes longer to form a regenerate. Phase 3 is the distraction phase. Ilizarov found that optimal bone regeneration occurs with a distraction rate of 0.25 mm 4 times a day (Fig. 2). Phase 4 is the final stage and is termed the consolidation phase. It is characterized by maturation and consolidation of the newly formed regenerate bone with the goal of achieving the capacity allowing full weight-bearing.[4] Typically, full weight-bearing is permitted when observing the regenerate cortical thickening at 3 of 4 cortices. With newer implants such as the PRECICE STRYDE, weight-bearing can be permitted before consolidation in some patients.

Differences between lengthening with external fixators and with ILN's can be divided into 2 aspects, biological and mechanical. Szymczuk et al[5] compared the ILN with a monolateral fixator in congenital femoral deficiency. They found that there were no differences in the quality of the regenerate as indicated by the distraction index, consolidation index, and fracture after removal of the implant. These results have been reproduced in another study,[6] with a heterogeneous patient population, including skeletal dysplasia and posttraumatic LLD. It was found that the healing index and time to full weight-bearing was shorter in the ILN group as compared with the monolateral fixator.

Mechanical differences between the external fixator and ILN include: (1) the lengthening axis, (2) the ability to span adjacent joints (knee, ankle) throughout lengthening, and (3) postoperative weight-bearing. External fixation lengthening can be tailored to lengthen along the anatomic or the mechanical axis, whereas using an ILN restricts lengthening to the anatomic axis. In the femur, lengthening along the anatomic axis can result in a lateral deviation of the mechanical axis (medialized knee joint) by about 1 mm for every 1 cm of lengthening. However, this has shown to be of minor consequences unless the deviation exceeds 10 mm.[7] A well-described complication of limb lengthening is joint subluxation that can occur with both fixators and ILNs. Conditions such as congenital femoral deficiency with knee instability increase the risk.[8] When using fixators for lengthening, there is an advantage of being able to apply a joint spanning external fixator, either prophylactically or as a treatment for subluxation once it occurs.[8,9] Although the application of a fixator over an ILN is possible, the risk of pin tract infections that could develop into an intramedullary infection is a serious concern. Weight-bearing after nail lengthening depends on the implant specifications, according to the manufacturer. For the PRECICE nail, the weight-bearing limit is 30 lb (13.6 kg) for an 8.5 mm diameter nail, 50 lb (22.7 kg) for a 10.7 mm diameter nail, and 70 lb (31.8 kg) for a 12.5 mm diameter nail until full consolidation.[10] Newer nails such as the PRECICE STRYDE nail may allow full weight-bearing postoperatively. However,

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FIGURE 1. Low energy osteotomy instruments. Osteotomy is performed with dedicated 8 to 10 mm osteotomes, a 13 mm wrench is utilized to rotate the osteotomes to ensure full release, a 4.8 mm drill bit with its drill guide is shown and is used to vent the medullary canal and penetrate the cortex at osteotomy site before passing the osteotomes.

that depends on the patient weight and diameter of the nail used. For external fixators, some surgeons allow partial weight-bearing, whereas others allow full weight-bearing from the first postoperative day.[6]

NAIL SELECTION

The factors involved in nail selection include entry point, nail length, and soft tissue thickness.[11,12] Entry points for femoral lengthening nails can be antegrade (piriformis or trochanteric entry) or retrograde. The piriformis entry nail may be used for skeletally mature patients, whereas trochanteric entry nails should be used for skeletally immature adolescents due to the risk of femoral head osteonecrosis.[13] For the tibia, an antegrade entry point is utilized. Indications for antegrade femoral nailing include LLD without deformity or with concomitant deformity in the proximal to middle femur. Retrograde femoral lengthening nails are indicated if antegrade nailing will result in excessive axis deviation, inability to introduce an antegrade lengthening nail, a concomitant distal femoral deformity, or an obese patient to bring the magnet to the distal thigh and closer to the skin (Fig. 3).[12,14] General contraindications for ILNs include an absent or narrow intramedullary canal, osteopenia due to the risk of locking screw pull out during lengthening, and infection in the form of current intramedullary sepsis.

Soft tissue thickness affects the use of ILN's because their lengthening mechanism works via energy transfer through the soft tissues. Hence the distance between the transmitter and the nail will impede energy transfer and lengthening. The maximum soft tissue distance between the fourth generation of the ERC4 for the 8.5 mm PRECICE femoral nail is 45 mm, and for the 10.7 mm nail is 75 mm, for the PRECICE tibial nail the maximum soft tissue distance for the 8.5 mm nail is 13 mm, and for the 10.7 mm nail is 16 mm.[15] Solutions to overcome this problem include pressing the ERC into the soft tissues and decreasing the distance traveled to the nail's magnet or placing the ERC skin target in the thinnest area along the equator of the limb. Lengthening the tibia typically does not pose this problem due to its subcutaneous anatomic nature.[11,16] The ILN's are limited in length and diameter; therefore, proper planning and preordering are essential. In terms of nail length, a principle is

FIGURE 2. Bony regenerate in femoral lengthening. A, Nail implanted and osteotomy performed. B, Regenerate at beginning of consolidation phase. C, Bony regenerate at the end of consolidation phase.

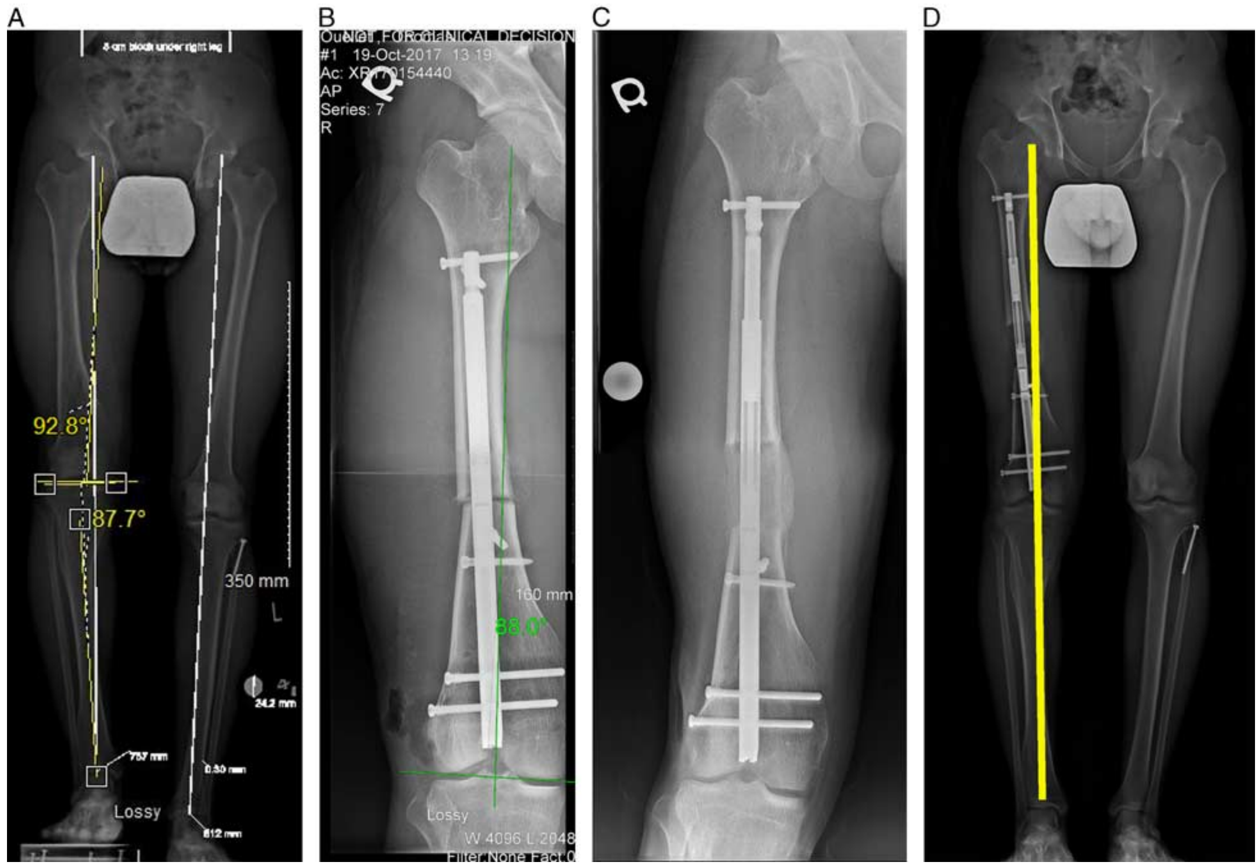

FIGURE 3. Distal femur osteotomy and retrograde intramedullary lengthening nail insertion. A, Preoperative image demonstrating medial mechanical axis deviation and a mechanical lateral distal femoral angle of 92.8 degrees in addition to a leg length discrepancy of 55 mm. B, Postoperative image in the anterior-posterior plane after deformity correction and nail insertion. C, Femur at end of distraction phase. D, Hip to ankle long film view showing correction of the mechanical axis.

to maintain 50 mm of the nail's thick part in the moving segment at the end of distraction to optimize the stability of the construct. The shortest nail possible for lengthening calculation is according to the following formula: 50 mm+30 mm+X+O, whereby X is the amount desired lengthening, and O is the distance from the entry point to the osteotomy (Fig. 4). When lengthening the femur, the location of the osteotomy is determined according to the presence of a concomitant deformity, and if no deformity is present, then the osteotomy is done at the apex of the femoral bow on the sagittal plane as determined by the lateral femur radiograph. This method overcomes the potential for mismatch between the nail and the femur, considering that all lengthening nails are straight due to the internal components, and do not have a bow corresponding to the femoral anatomy as in the trauma nails. Shorter nails can avoid the issue of mismatch between the nail and the femur, and they allow the option of peri-implant lengthening as in below a total hip arthroplasty.[17]

BLOCKING SCREWS

The use of blocking screws (poller screws) as an aid for intramedullary nail fixation of femur and tibia fractures is a common surgical technique that was first described by Krettek et al.[18] The function of blocking screws is to improve the alignment of bone segments and enhance the stability of the ILN fixation. By being placed adjacent to the nail tract, they help direct the nail during insertion and assist in controlling deformity correction. Furthermore, by reducing relative motion between the bone and the ILN, they enhance the stability of the construct.[19] Limb lengthening surgery is often combined with deformity correction in the coronal, sagittal, or axial planes. When corrective osteotomies are performed in the metaphyseal region of the bone, the width of the nail does not occupy the medullary canal hence creating potential instability and deformity; utilizing blocking screws in this setting helps stabilize the ILN.[14,20] The locking bolts of limb lengthening nails are smooth and are threaded only at the cortex for maximal stiffness, and this can allow undesirable translation of the nail over the locking bolt, creating angular deformity during lengthening.[12] Due to muscle deforming forces, there are typical lengthening related deformities that are specific to the bone lengthened and the site of the osteotomy. Proximal femur lengthening with an antegrade nail tends to create varus, retrograde nailing of the distal femur tends to create flexion (procurvatum), and lengthening of the tibia typically creates valgus-procurvatum.[21] Accurate preoperative planning and correct positioning of the blocking screws intraoperatively will facilitate correction of the deformity, secure the achieved deformity correction while lengthening, and prevent lengthening-induced new deformities (Fig. 5). When using blocking screws, reaming over the guidewire should be done after positioning the screws to ensure the correct tract for the nail to follow and allow correction of the deformity and maintenance of alignment.

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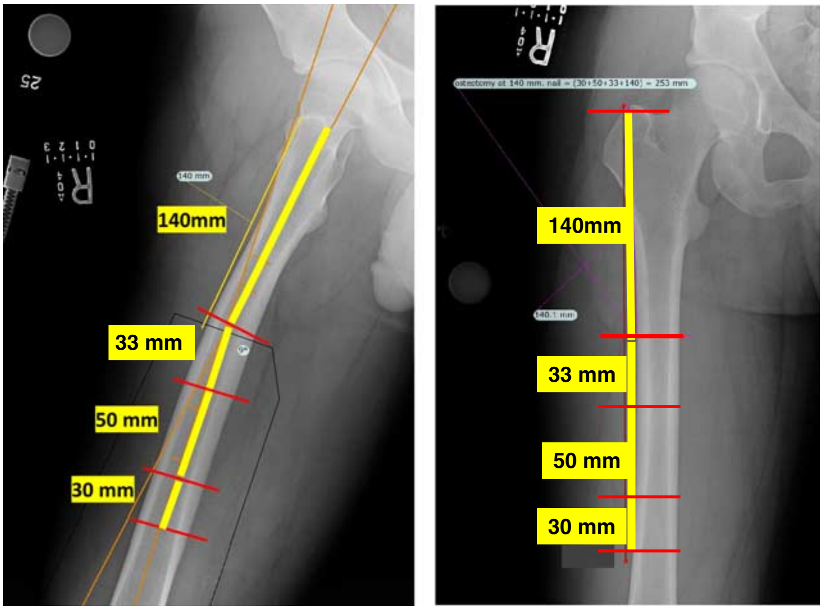

FIGURE 4. Example shown to calculate the shortest nail length (SNL) = osteotomy distance+lengthening planned+50 mm+30 mm. SNL = 140+33+50+30, SNL = 253 mm. The desired lengthening is 33 mm, distance from entry point to osteotomy is 140 mm, 30 mm is added for the protruding part of the nail and 50 mm added to maintain adequate stability of the construct after distraction.

Coronal plane deformities are addressed with blocking screws that are oriented anteroposteriorly, whereas sagittal plane deformities are treated with blocking screws oriented in the mediolateral plane. Several methods have been described to determine the number of blocking screws and their exact location to maximize their efficiency.[22,23] Muthusamy et al[21] presented the practical "reverse rule of thumbs" to help the surgeon determine the ideal position of blocking screws by envisioning the force needed to be generated on the bone segments to correct the deformity or prevent potential deformity. Another simple rule is to place the blocking screws adjacent to the osteotomy on the concave side of the deformity.

SOFT TISSUE RELEASES

Soft tissue releases in limb lengthening surgery are performed prophylactically to prevent nerve palsies, joint contractures, and joint subluxations/dislocations or performed if these complications develop during the lengthening process. Indicating a patient for a prophylactic soft tissue release can occur if the prelengthening clinical examination demonstrates nerve compression, joint contracture, or joint subluxation.[11] Certain risk factors have been studied and present a higher risk of these complications. Nogueira et al[24] found several factors that increase the risk of nerve injury with tibial lengthening: skeletal dysplasia, performing a double level tibial lengthening, and tibial lengthening with an associated deformity correction of > 10 degrees and especially a valgus deformity in the proximal tibia. Regarding joint contracture and subluxation, Rozbruch et al[25] found that an absolute tibial lengthening > 42 mm, the proportion of lengthening > 13% of the bone segment length, a congenital etiology and increased age were all risk factors in developing ankle joint contractures. In the case of femoral lengthening, the prevalence of nerve injury with a single level lengthening was found in a series of 214 lengthened femora to be 2%.[24] It has been shown that performing a prophylactic iliotibial band release with femoral lengthening, especially in the case of congenital etiologies or lengthening > 3 cm, is a prudent measure.[5,26] The gamut of soft tissue releases related to lengthening procedures includes peroneal nerve decompression, tarsal tunnel decompression,[27] rectus femoris release for hip flexion contracture, iliotibial band release for hip abduction contracture and knee flexion contracture, hamstring release for knee flexion contracture,[11] quadricepsplasty for knee extension contractures,[28] and gastrocsoleus release for equinus contracture.[25] There are other nonsurgical methods described for the management of nerve palsies and joint contractures, which include slowing or reversing the distraction for nerve palsies, aggressive physical therapy, and botox injections for contractures.[29]

PHYSICAL THERAPY

Physical therapy plays a significant role in limb lengthening. The lengthening process poses unique demands and considerations for the rehabilitation of the patient. During lengthening, muscle and tendons stretch progressively, leading to potential complications that include muscle weakness, joint stiffness, and contractures, or even joint dislocation.[30,31]

Loss of knee range of motion and joint contracture have been shown to be more common when lengthening the femur rather than the tibia.[32,33] Bhave and colleagues showed that knee motion and strength after femoral lengthening were not dependent on the amount of lengthening or the percent of lengthening. Also, it was shown that patients with congenital causes of LLD were most susceptible to joint stiffness after lengthening.[34] The role of physical therapy in limb lengthening is to maintain range of motion in adjacent joints, prevent contractures, strengthen muscles, and improve mobility and independent function of the patient.[35] In the early postoperative period, physical therapy should focus on guiding the patient regarding weight-bearing precautions and ambulation with assistive devices. Resting splints and orthotic intervention can be utilized for adjacent joints. Early joint mobilization is crucial

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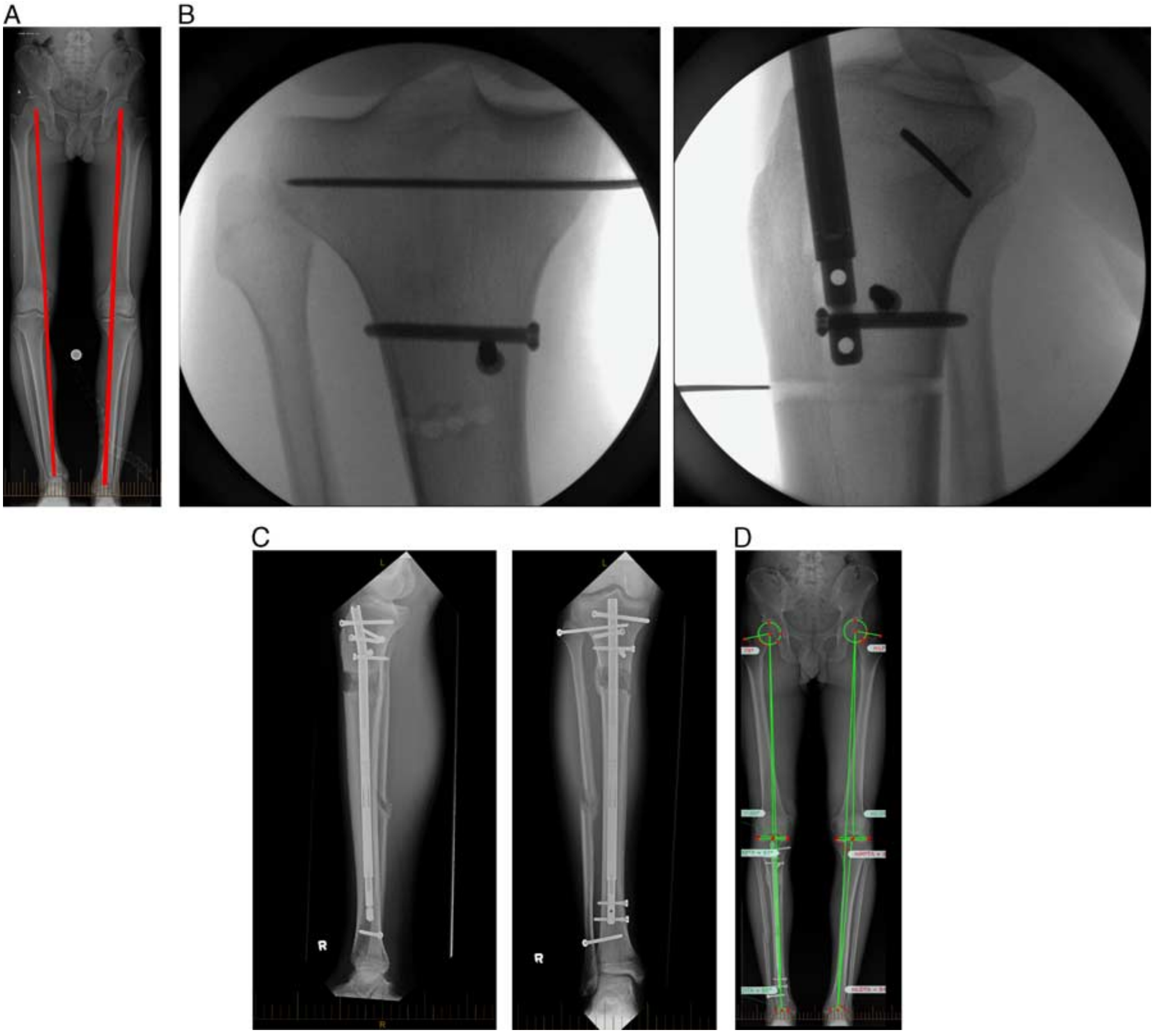

FIGURE 5. Blocking screws in the correction of proximal tibial varus deformity. A, Preoperative long film demonstrating bilateral proximal tibial varus deformities. B, Intraoperative anteroposterior image with 2 blocking screws inserted. C, Intraoperative lateral image with nail being inserted and guided by the blocking screws. D, Postoperative long film showing a neutral mechanical axis and medial proximal tibial angle of 87 degrees.

to prevent contractures, as it was shown in one study that the greatest loss of knee motion occurs in the latency phase.[31] During the lengthening and consolidation phases, the goals of physical therapy are to maximize joint range of motion, improve strength, and maintain muscle tone and flexibility. In addition, patients should be considered for splinting or bracing from the time of surgery prophylactically and therapeutically in situations where contractures develop during lengthening.

Rehabilitation may also include hydrotherapy for promoting an increased range of motion and muscle strength. Once weight-bearing is initiated according to the guidelines and surgeon's discretion, gait training, and return to normative function with appropriate use of the limb are the focus of therapy.

SUMMARY

Motorized ILNs utilize the basic principles of distraction osteogenesis, as described by Gavril Ilizarov. Differences between using ILN's and a monolateral fixator include that ILN's lengthen along the anatomic axis, which results in mechanical axis deviation, greater limitation in maximum patient bodyweight that is allowed when using ILN's, and in postoperative weight-bearing which is not permitted in ILN's until the consolidation phase. Many of the limitations are currently changing with newer implants as in the PRECICE STRYDE nail. Nail features in terms of entry point and nail length provide the surgeon with the versatility needed to tailor the surgery to the specific patients' needs and challenges. Adjunct procedures used in conjunction with ILN's include blocking screws and soft tissue releases, which aid in deformity correction and to prevent and treat contractures and neurovascular compromise, respectively. The role of physical therapy is vital and focuses on maintaining muscle strength, range of motion, and prevention of contractures.

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