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Motorized Internal Lengthening of Long Bones: Residual Limb Lengthening

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Summary: Distraction osteogenesis can be performed for transfemoral amputees using a motorized intramedullary limb lengthening nail (LLN) such as the 14×130 mm NuVasive Freedom nail. Despite being the shortest commercially available LLN, some patients have even shorter residual femurs, making it impossible to link the bone to the nail by the standard technique of inserting a cross-locking bolt through the proximal and distal nail holes. Two modified techniques of linking a very short femur to a LLN are introduced in this manuscript. The triple cable lasso technique passes 2 cerclage cables transversely through the cortex and then the nail hole, with a third cable clamping the first 2 to the outer cortex. The contoured locking plate technique bends a locking plate to fit over the protruding distal tip of the nail, locks a screw in the plate which threads the distal nail hole, and then locks the plate to the bone with unicortical screws.

Key Words: limb lengthening—motorized nail—osseointegration—amputation—transfemoral—above knee amputation—Freedom nail.

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INDICATIONS

Limb lengthening, utilizing distraction osteogenesis, can be performed for amputees as well as for patients with complete limbs. The 2 most common indications for lengthening a patient's residual femur following amputation are (1) to improve the geometry of a residual limb to facilitate better fit of a traditional socket prosthesis (TSP), and (2) to fully contain a standard osseointegration implant. Traditionally, lengthening was performed with an external fixator, but the development of motorized telescopic intramedullary limb lengthening nails (LLNs) has been a tremendous advance for all surgeons with an interest in limb reconstruction.[1–8] Short residual limbs inherently provide less mechanical advantage and prosthesis control than longer residual limbs.[9–12] Although a TSP can address limb length discrepancy following amputation via pylon adjustment, excessively short limbs impede proper socket fit due in part to the limb's spheroid instead of cylindrical shape. Accordingly, a residual limb that is far too short to allow a stable and comfortable TSP suspension can be an indication for limb lengthening.

For amputees considering skeletal transcutaneous osseointegration (STOI), external soft tissue geometry is a lesser consideration, as there is no socket. Lengthening before STOI is most commonly indicated when the recipient bone is too short to accept a standard implant. Standard implants are preferable to custom designs because custom options are more expensive, offer less quality control,[13] and can limit available intraoperative options to accommodate unexpected anatomy or other situations.[14] The 2 osseointegration implants used by the authors are press-fit nail-type implants 140 mm long (integrated limb prosthesis; Orthodynamic, Lubeck, Germany) or 160 mm long (osseointegrated prosthetic limb; Permedica Medical Manufacturing, Lecco, Italy). The implant selection process reflects a complex decision involving the surgeon's choice and clinical exigency to address the specific needs of each patient and is beyond the scope of this article. STOI implants and principles are fully described in a recent review article.[15]

The shortest LLN currently available is the Freedom Residual Limb Lengthening device (NuVasive, San Diego, CA), at 14×130 mm. The key features are a telescoping design with 3 total chambers capable of lengthening 100 mm, and an internal drive mechanism that lengthens in a stepwise manner. The Freedom nail is powered by a magnetic field generated by a device that sits outside the patient's limb, called an External Remote Controller. There is one stabilizing hole at each end of the nail which is designed to accept a cross-lock bolt.

Despite being the shortest LLN, some patients' residual bone is even shorter, and the routine technique of a cross-lock bolt in each hole cannot be performed. This article describes 2 modified techniques and the protocols associated with transfemoral amputee lengthening using a Freedom nail for femurs shorter than the 130 mm nail. The indication for lengthening for all patients was to eventually receive a STOI.

Surgical Planning

Surgical planning for lengthening in amputees generally requires attention to the same factors as for nonamputees. The following principles are the most critical: patient engagement, nutrition, health optimization, and social support must be assured before starting the process; preoperative templating must be accurate to determine length goals and implant needs and also to ensure the eventual additional prosthesis components will be available; an uninterrupted time period must be chosen to perform lengthening and consolidation; and the patient must have access to imaging resources to follow lengthening progress and also access to their surgeon should an unforeseen circumstance arise. Because the common principles are discussed in depth by other articles in this issue, this article will focus on the unique concepts for amputee

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For reprint requests, or additional information and guidance on the techniques described in the article, please contact Jason S. Hoellwarth, MD, at drjsoon@gmail.com or by mail at Mailing address: Norwest Advanced Orthopaedics, Norwest Private Hospital—Ground floor Suite 3B, 9 Norbrik Drive, Bella Vista, NSW 2153, Australia. You may inquire whether the author(s) will agree to phone conferences and/or visits regarding these techniques.

TABLE 1. Tips for Success

Goal	How to Achieve
Patient compliance	Preoperative consultation with a psychologist to ensure resilient and disciplined behavior. Plan for financial and employment security. Patients should secure social support (family or friends). Counsel patients with a generous time frame necessary for uninterrupted lengthening
Pain control	Minimize preprocedure narcotic use. Identify treatable sources of pain (eg, lumbar stenosis or neuroma). Consider preoperative evaluation by a pain specialist
Equipment management	Train patients in External Remote Controller use before hospital discharge
Patient mobility and independence	Consider preoperative evaluation with a physical therapist for gait or wheelchair training. Consider occupational therapist consultation for modified activities for daily living

lengthening in preparation for STOI: templating, physical examination, and surgical techniques. A summary of tips for success (Table 1) and recommendations for avoiding pitfalls (Table 2) are provided.

The essential goal for amputee lengthening before STOI is to create a bone with a canal long enough for the chosen implant: 140 mm for integrated limb prosthesis, and 160 mm for osseointegrated prosthetic limb. Although STOI has been successful at shorter lengths, achieving maximum implant coverage provides the following benefits over a shorter canal: improved axial alignment during insertion, greater surface area for bone ingrowth, reduced early motion, and a stronger lever arm to power the extremity. In addition, should a patient sustain a periprosthetic fracture following osseointegration, a longer bone increases the reconstruction options and the chance of implant retention.[16]

During the templating phase, a multidisciplinary team including a prosthetist helps to consider both endoprosthesis and exoprosthesis factors before lengthening. Because STOI implants can be connected to almost any external prosthesis model, the principles of external prosthesis choice are similar to standard principles[17] and are not discussed here. The key concept is that the prosthetic knee joint line should match the native knee joint line in unilateral amputees. Thus, the amputated femur must leave enough room to accommodate both the osseointegrated endoprosthesis and the external prosthetic limb. For patients with bilateral transfemoral amputations, knee joint line, and leg lengths can be modified to the preference of the patient and prosthetist. In all situations, the surgeon and prosthetist should agree on a target femur length during the templating phase.

Limb length measurement must be based on imaging modalities that are both accurate and precise. The authors recommend leg length comparison by traditional full length standing radiographs.[18] The patient's pelvis should be leveled to facilitate proper measurement of the length from the piriformis fossa to knee joint line. If a patient has a radiolucent TSP, that may be a convenient tool to level the pelvis. A marker of known size should be placed at the same distance from the radiographic plate as the patient's femur, similar to total joint templating radiographs, to correct for magnification effects. The authors also perform a computed tomography scan of the operative femur for STOI 3-dimensional templating purposes.[19]

TABLE 2. Avoiding Pitfalls

Pitfall	Avoidance or Management
Inadequate regenerate	Avoidance: Do not exceed 0.5-1 mm daily lengthening split into 3-4 sessions (program ERC limits when possible). Minimize patient activity and weight-bearing (prevent motion at regenerate site). Optimize patient nutrition. Weekly radiographs to assess regenerate Management: Slowly continue lengthening to goal (to get soft tissues to length). Consider a consolidation period of 1-2 mo to allow potential bone formation. If inadequate evidence of regenerate formation, perform open bone graft placement over the nail. Common sources include the contralateral femur reamed irrigator aspirator or iliac crest
Early consolidation	Avoidance: Maintain regular lengthening several times daily. Weekly radiographs to identify hyperdense regenerate appearance Management: Repeat corticotomy with reduced or no waiting period before restarting lengthening
Malalignment	Avoidance: Insert nail with thickest component in the proximal, stable bone segment (antegrade orientation). Place blocking screws to snugly maintain nail position. Place blocking screws in the distal bone segment surrounding the nail, when possible Management: Often the eventual prosthesis can accommodate modest malalignment. A reorienting osteotomy may be necessary for severe malalignment
Nail migration	Avoidance: Place "backup" blocking screws proximal and distal to the nail in line with lengthening Management: Stop lengthening. Depending on length achieved, observe or reoperate
Failure to lengthen	Avoidance: Ensure complete corticotomy (gross lateral displacement on image intensifier). Check that nail lengthens before inserting by using high-speed drill-powered lengthener before inserting. Confirm nail and bone lengthen together in situ using ERC Management: Ensure the ERC is located over the nail's lengthening mechanism and orientation is correct (not backwards). Ensure ERC is creating an adequate magnetic field. Carefully measure imaging, correcting for magnification. If all nonoperative troubleshooting fails to correct the issue, surgical inspection to troubleshoot is required

ERC indicates External Remote Controller.

Before lengthening an amputated femur, the following physical examination points are important to check. Because the authors recommend inserting the LLN retrograde through the distal canal, this skin should be checked to identify any potential issues such as very thin skin or adherence to the femur, or the presence of wounds that must heal before surgery or should be excised. Specifically, for patients whose femur is shorter than the LLN (130 mm), the skin envelope must be sufficient to close the incision over any additional hardware used to link the LLN to the bone.

Finally, the authors emphasize the importance of considering factors beyond direct surgical issues. Preoperative psychological counseling, planning for pain management, social support, and employment or financial security are all important considerations with respect to optimizing outcomes.

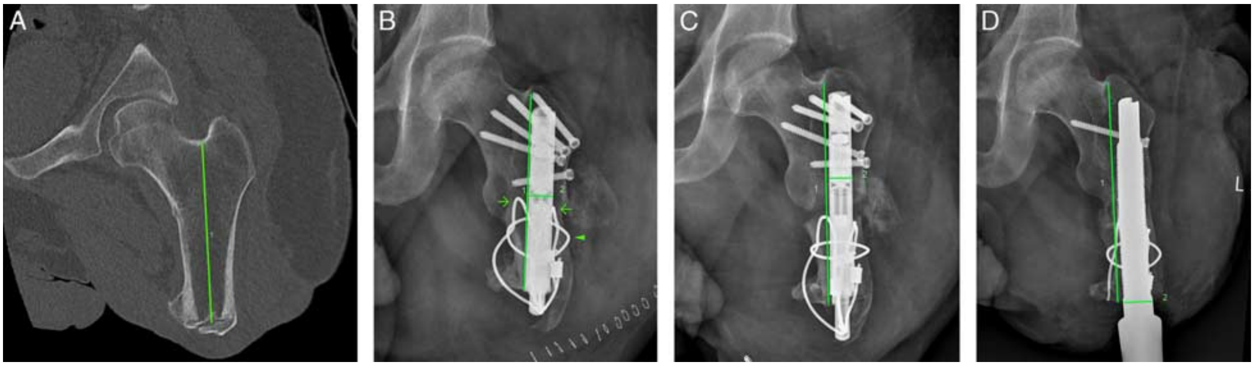

FIGURE 1. Triple cable lasso technique. This patient was a 41-year-old male with left transfemoral amputation 2 years prior. A, Templating computed tomography Line 1 from piriformis fossa to distal bone end measured 114 mm, shorter than the 130 mm lengthening nail. The goal was to achieve a 140 mm long canal (a minimum gain of 26 mm). B, The nail extended beyond the femur, so the following technique was used to link the nail to the distal femur segment. Two holes were drilled in the distal segment, each passing transcortically through both the lateral and medial cortices. One cable was passed through each pair of drill holes, then through the distal limb lengthening nail (LLN) hole (indicated by arrows). Both cables were gently tightened and routinely secured. Because bone amputated years before can be osteopenic, these cables can cut through after initiating distraction. Thus, a circumferential cable (indicated by arrowhead) secured the 2 longitudinal cables to the distal segment, capturing them transversely around the strongest portion of the remaining bone, the cortex. C, Routine postoperative lengthening protocol followed, and no issues arose, achieving a final distraction length measuring 137 mm. D, Standard integrated limb prosthesis implant 18×140 mm implanted 392 days after LLN insertion. Currently, 37 months following LLN surgery, no setbacks have occurred.

Surgical Technique

Although each amputee's surgery requires slight variations, the following technique generally can be followed.

Make a generous incision to provide clear exposure of the distal femur, and excise redundant soft tissue, fat, and scars as needed. Percutaneously vent the femur just distal to the lesser trochanter using a drill. Insert a guidewire retrograde through the residual femur and perform progressive reaming to 15 mm, 1 mm greater than the LLN. Insert the nail, in an antegrade orientation, but retrograde through the distal exposure, to the osteotomy level. Complete the osteotomy with a low energy technique such as an osteotome or a Gigli saw[20–24] to preserve periosteum. Fully insert the LLN to the desired position (usually to the piriformis fossa). Apply bone reamings to the osteotomy site when possible. The proximal cross-lock hole can usually be secured with a bolt or screw. An additional blocking screw or bolt should be inserted just proximal to the nail to prevent inadvertent migration through the piriformis fossa during lengthening. Additional blocking screws should be placed in the residual femur as needed to stabilize the nail and provide the straightest trajectory possible. Ideally, blocking screws can be placed in both the proximal and distal segments. The nail should typically be placed in an antegrade orientation because the proximal portion of the nail is the outermost casing and does not elongate. Thus, if its position can be stabilized then the straightest lengthening can be achieved. If the nail is inserted in a retrograde orientation, as the nail segments telescope the remnant proximal portion will be the thinner inner tubes and this construct will become less constrained and can result in angular deviation. For femurs with at least 130 mm starting length, a bolt or screw can be inserted into the distal cross lock hole. For femurs that are shorter than the nail, 2 modified linkage techniques are shown and described in Figures 1 and 2.

Postoperative Routine

Distraction normally begins following a 5- to 7-day latency period which allows the acute inflammatory phase to resolve. The osteotomy ends are gradually mechanically distracted at a controlled rate and rhythm, typically 0.5 to 1 mm daily in 3 or 4 equally divided increments. Patients are informed to alert the surgeon if experiencing increased operative site pain, hip pain or decreased hip motion, or systemic symptoms. Weekly or bi-weekly radiographs during the distraction phase permits monitoring of bone length and regenerate quality.[25]

During lengthening, active physiotherapy is critical to maintain hip joint motion and to prevent or minimize progression of contractures. Maintaining or improving hip abduction and extension is paramount, but care must be given to not overly stress the regenerate and disrupt osteogenesis. Whereas Ilizarov emphasized loading the limb in the frame,[20,21] the Freedom nail is not designed for weight-bearing. To minimize torque to the nail construct, avoid passively moving the extremity from the distal portion; instead, gently move the limb holding as proximal as possible. Lying prone on a firm surface (to avoid sinking in) is a convenient strategy for many patients to stretch the hip flexors. If the osteotomy is below the gluteus maximus insertion, active hip extension may be beneficial.

Once the desired length is achieved the regenerate bone is allowed to consolidate radiographically until at least 3 cortices have been restored. Subsequently, LLN removal and osseointegration is performed in a single surgery. STOI rehabilitation follows a separate protocol.[26]

Outcomes

Surgical parameters and outcomes for 9 amputees who had lengthening using one of the modified techniques with the goal for eventual osseointegration are presented (Table 3). All eventually achieved adequate length and underwent successful insertion of a standard osseointegration implant. The intended amount of lengthening varied widely among patients. The triple cable lasso technique was conceived of and implemented before the contoured locking plate technique, leading to its greater representation. Seven patients (78%) experienced a complication requiring surgical intervention, the most common being inadequate regenerate (5 patients, 56%). Management consisted of open surgical inspection and

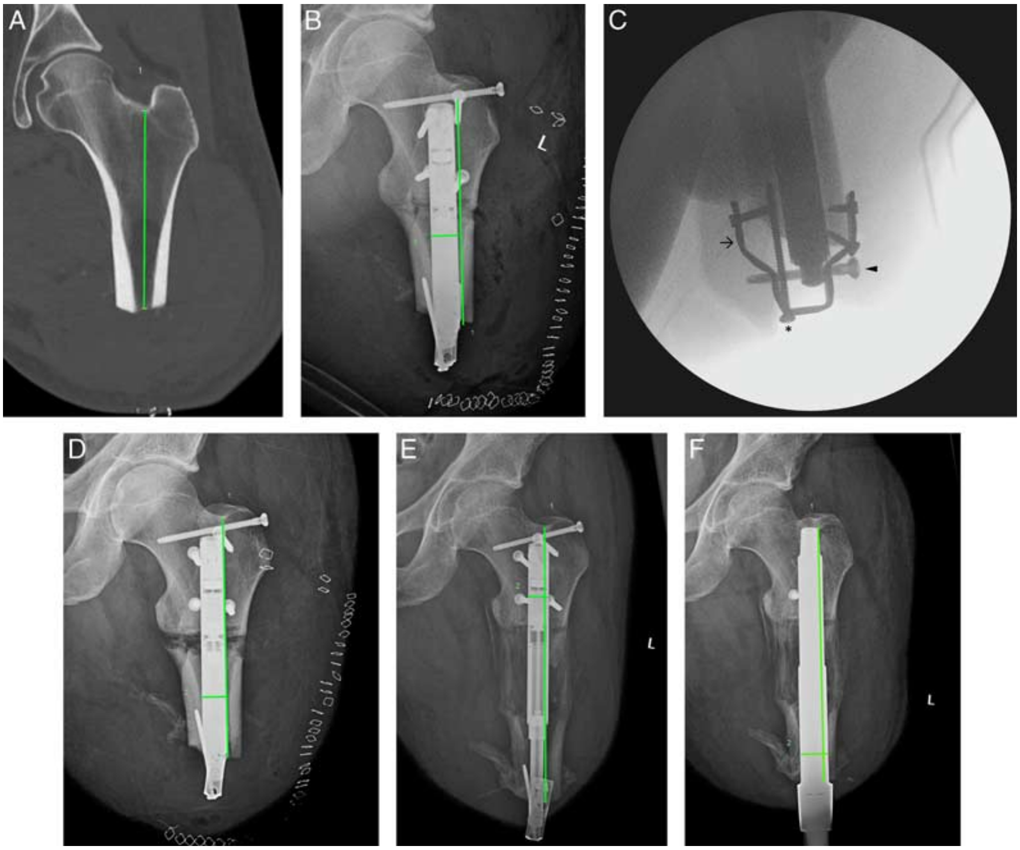

FIGURE 2. Contoured locking plate technique. This patient was a 46-year-old male transferred to our hospital several weeks after having bilateral transfemoral amputation performed after sustaining a farm injury. The right femur was sufficiently long for a standard osseointegration implant, but the left was not. A, Templating computed tomography Line 1 from piriformis fossa to distal bone end measured 124 mm, shorter than the 130 mm lengthening nail. The goal was to achieve a 140 mm long canal (a gain of 16 mm). B and C, A one third tubular locking plate (indicated by arrow) was contoured around the distal femur which allowed one screw (indicated by arrowhead) to capture the distal limb lengthening nail (LLN) hole. One long intracortical screw (indicated by asterisk) and 3 additional unicortical screws linked the nail to the distal bone segment. The routine postoperative lengthening protocol was initiated but lengthening immediately caused severe pain without length gain. D, Direct inspection of the construct identified that one of the screws securing the plate to the distal segment cortex interfered with a telescoping segment of the nail. The screws were repositioned and a new nail was placed. Elongation was confirmed in situ before closure. E, Further lengthening was uneventful to 164 mm. F, The LLN was exchanged for an osseointegrated prosthetic limb 19×160 mm 112 days after LLN insertion. Currently, 11 months following his LLN surgery, no other setbacks have occurred.

TABLE 3. Results of Limb Lengthening Treatment for Transfemoral Amputees

Variables	n (%)/Mean [SD (Range)], N = 9 Patients
Original femur length (mm)	96.6 [32.6 (25-135)]
Gain goal (mm)	43.4 [32.6 (5-115)]
Final femur length (mm)	149.4 [33.8 (90-197)]
Length gained (mm)	52.9 [23.2 (23-105)]
Goal length % achieved	231.2 [339.2 (66.7-219.2)]
Complication-free lengthening	2 (22)
Complications	
Interim nonunion	5 (56)
Early consolidation	1 (11)
Mechanical failure	1 (11)
Time from limb lengthening nail to OI (d)	366.2 [121.4 (112-510)]
Nail retention technique	
Triple cable	7 (78)
Plate and screw	2 (22)

OI indicates osseointegration.

autograft application over the LLN. One patient's autograft was harvested from the ipsilateral anterior iliac crest; the graft for the other 4 was obtained via contralateral femur reamed irrigation aspirator. All patients performed no further lengthening, and staged osseointegration occurred when the regenerate appeared radiographically consolidated on 4 cortices. The average time from the first lengthening surgery to osseointegration was 1 year (366.2 d).

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