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Bone Transport versus Acute Shortening for the Management of Infected Tibial Non-Unions with Bone Defects

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Statement:

None of the authors do have any financial interest, any other relationship with a commercial company or a conflict of interest related directly or indirectly to this research.
Abstract

Introduction:

This study compared bone transport to acute shortening/lengthening in a series of infected tibial segmental defects for infected tibial non-union.

Methods:

In a retrospective comparative study 42 patients treated for infected tibial non-union with segmental bone loss measuring between 3 and 10 cm were included. Group A was treated with bone transport and Group B with acute shortening/lengthening. All patients were treated by Ilizarov methods for gradual correction as bi-focal or tri-focal treatment; the treating surgeon selected either transport or acute shortening based on clinical considerations. The principle outcome measure was the external fixation index (EFI); secondary outcome measures included functional and bone results, and complication rates.

Results:

The mean size of the bone defect was 7 cm in Group A, and 5.8 cm in Group B. The mean time in external fixation in Group A was 12.5 months, and in Group B was 10.1 months. The external fixation index (EFI) measured 1.8 months/cm in Group A and 1.7 months/cm in Group B. Minor complications were 1.2 per patient in the transport group and 0.5 per patient in the acute shortening group (P = 0.00001). Major complications were 1.0 per patient in the transport group versus 0.4 per patient in the acute shortening group (P = 0.0002). Complications with permanent residual effects (sequelae) were 0.5 per patient in the transport group versus 0.3 per patient in the acute shortening group (P = 0.28).

Conclusions: While both techniques demonstrated excellent results, acute shortening/lengthening demonstrated a lower rate of complications and a slightly better
radiographic outcome. Bone grafting of the docking site was often required with both procedures.

**Keywords:** infected non-union; osteomyelitis; segmental defects; acute shortening; bone transport; bone lengthening; Ilizarov method; distraction osteogenesis; external fixation; limb salvage

**Level of evidence**

Level III; retrospective comparative study

**Introduction**

Infected tibial non-uniøns have always been extremely difficult to manage successfully, and this challenge is magnified when a segment of bone is absent [1-6]. Chronic osteomyelitis may require additional resection of necrotic bone to eradicate an active nidus of infection [7,8]. Major soft-tissue injuries, deformity, or a leg-length discrepancy can significantly influence the functional outcome and may further complicate the presentation. They are often the consequence of high-energy trauma and many have already failed to respond to multiple prior surgical procedures, resulting in further soft tissue compromise. This may impair local vascularity surrounding the non-union, exposing the limb to greater risk of treatment failure [7,8]. Underlying host factors such as smoking or diabetes may further compromise conditions.

There are several treatment options available to manage patients who have tibial non-uniøns with bone defects in the presence or absence of infection [1, 9-13]. These include cancellous bone grafting [4,14-16], Papineau open cancellous bone grafting [17], vascularized free-tissue transfers [18-20], and combined approaches with both microvascular tissue transfers and bone grafts [3]. Masquelet developed the induced membrane technique almost 20 years ago, to enhance graft incorporation [21,22]. However, acute corrections are often limited by soft tissue constraints, and these methods may not allow the surgeon to completely correct alignment and restore limb length. Regardless of the
option selected, treatment times associated with limb salvage are usually long with frequent complications [4, 14-16, 23-25]. Alternatively, amputation may be considered a reasonable surgical reconstructive option for those patients who seek a definitive procedure with a more predictable outcome [7,8,26,27].

Distraction histogenesis [25,28-30] techniques and methods using external fixation for gradual correction have dramatically expanded the options available for the treatment of tibial non-unions and associated bone defects [1,2,9-12,23,31-35]. These methods, pioneered by Ilizarov [29,32], have been used successfully outside Russia for over 30 years [1,2,15,16,34-36]. In contrast to other methods, these techniques can simultaneously address the multiple elements of pathology including shortening, deformity, bone loss, joint contractures, and some soft tissue defects. The Ilizarov method for the treatment of tibial non-unions associated with bone defects generally involves bifocal or trifocal osteosynthesis [1,34], compressing bone at one level to achieve union while simultaneously applying distraction to the same bone at another level to regenerate bone mass. These Ilizarov methods of limb salvage include both bone transport [1,4,5,7,9-12,34,36-43] and acute shortening/lengthening [5,7-9,36,44-48].

Bone transport is characterized by the gradual translocation of a segment of bone, often together with its surrounding soft tissue envelope, from an adjacent healthy area into the region of bone loss [1,4,5,7,9-12,36-43]. A low energy osteotomy or corticotomy [29,30,49] is performed at a location outside the zone of injury, and the external fixator used to gradually transport the bone segment under carefully controlled mechanical conditions. As the bone defect gradually becomes smaller the process of distraction osteogenesis generates new bone in the distraction gap, restoring bone mass and skeletal continuity [29,30]. The hallmark of bone transport is that the length of the limb does not change since the rate of lengthening in the distraction gap is equal to the rate of shortening at the bone defect site.
Acute shortening/lengthening is characterized by shortening of the limb through the region of the bone defect itself, and can be performed acutely, gradually, or as a combination [5,9-12,36,44-48]. The shortened limb is concurrently lengthened to equalize limb lengths through bifocal osteosynthesis, analogous to the technique used for bone transport. An external fixator is used to apply compression across the defect to achieve union, and length is gradually restored by simultaneous distraction through an osteotomy at another level. The hallmark of acute shortening/lengthening is the early contact across the original area of bone loss [5,9-12,36,44-48]. This early compression enhances the mechanical stability of the bone-fixator composite, and offers the potential of more rapid union resulting from immediate contact. Recent publications discussing this approach have unfortunately suffered from limitations in study design and sample size, or have been less robust statistically [45-48].

Soft tissue and vascular considerations dictate the extent of acute correction possible. Cases with large bone defects are generally treated by bone transport, and cases with small bone defects are more often treated by acute shortening/lengthening. The purpose of this study was to compare bone transport to acute shortening/lengthening in the treatment of a series of cases of tibial segmental defects. We hypothesized that acute shortening/lengthening would result in fewer docking site complications and procedures, and a shortened treatment time, compared to bone transport.

**Materials and Methods**

**Study Design**

This retrospective non-randomized comparative study was based on hospital records and analysis of routine radiographs obtained during the course of treatment. This project was part of a clinical audit and exempted from IRB approval. Inclusion criteria were adult patients with post-traumatic tibial non-unions with bone loss measuring between 3 and 10 cm. Patients were excluded if the medical record
was incomplete or follow-up was less than one year. Surgery was conducted by three experienced Ilizarov surgeons at multiple sites all within a single medical system in Baltimore, MD, USA. All patients were managed using Ilizarov methods and the Ilizarov circular external fixator (Smith & Nephew, Memphis, TN), either by bone transport or acute shortening/lengthening. Treatment selection was based on clinical parameters according to surgeon judgment, individualized to the specifics of each particular case. Some of the patients in the bone transport group were already included in the study cohort of a prior publication dedicated to that technique [39].

The total bone loss was calculated as the sum of the length of the bone defect and the magnitude of any limb length discrepancy, if present. The radiographic consolidation time for the distraction gap was measured according to the criteria of Fischgrund, et al. [28]. The principle outcome measure was the external fixation index (EFI), determined by dividing the time in external fixation by the length of bone regenerated (in months/cm). Clinical outcomes were divided into bone results and functional results according to the evaluation system previously reported by Paley & Maar [39]. Complications were recorded, and these were considered either minor (treated non-operatively), major (treated operatively), or sequelae (unresolved after treatment) [24].

**Surgical Considerations**

Detailed descriptions of the surgical techniques for bone transport [39,42,43] and acute shortening/lengthening [44,48] have been published previously. Cases with large bone defects (>10 cm) are generally treated by bone transport, while small bone defects (<3 cm) are most often treated by acute shortening/lengthening. Soft tissue and vascular considerations generally dictate the extent of acute correction possible, when indicated. Despite its more direct nature acute shortening/lengthening should be considered the more technically demanding procedure, particularly in cases with bone defects exceeding 4 cm. Acute shortening requires additional soft tissue dissection,
while bone transport is a less extensive procedure with no need to expose the fibula. The immediate risk is often greater with acute shortening compared to bone transport, with an increased possibility of catastrophic vascular injury. Although no vascular injuries were encountered in this series, it remains a genuine risk and the vascular response to shortening must be monitored carefully. If any significant change in circulation was identified after acute shortening, the limb was lengthened a centimeter and circulation reassessed. The residual bone defect was then managed by gradual shortening at a relatively rapid rate (2-3 mm/day) over the next two weeks. Dense scarred soft tissues must be resected completely prior to the acute shortening, or it may obstruct docking and limit the magnitude of shortening. This additional dissection itself increases the risk of iatrogenic vascular damage, and must be undertaken with some care and respect for distorted anatomy. The risk of anterior tibial or peroneal artery damage is significant with partial resection of the fibula, especially if attempted through the same anterior incision used to approach the tibia.

Acute shortening is generally done through a transverse incision to facilitate wound closure. Longitudinal incisions gap open as the limb is acutely shortened, and can make wound closure difficult or impossible. Transverse incisions are far more amenable to acute shortening and facilitate closure without tension. A transverse incision can make deep dissection slightly more difficult, although this is a minor issue. However, the transverse component often will need to cross prior longitudinal incisions and it must be made with care. Acute shortening in the presence of a mature free flap can only be done with resection of part of the flap in a transverse manner, and should be performed with caution.

The status of the fibula is an important aspect, and must be considered when determining whether to choose reconstruction using either bone transport or acute shortening/lengthening. When the fibula is intact bone transport is generally the preferred option, and this preserves the normal length of the leg while minimizing the amount of dissection and time required to complete surgery. When the fibula has a substantial defect that is greater than the size of the tibial defect, acute shortening is more attractive.
Following an acute injury the fibula is often also fractured, and this can frequently be allowed to shorten with bayonet apposition of the fibula fracture site. If the fibula has united in a malreduced position any shortening or malrotation may lead to symptoms influencing clinical outcomes, particularly in the distal quarter of the leg. In this situation, it is sensible to consider acute shortening/lengthening after osteotomizing the fibula and correcting the malorientation of the distal fragment.

There is often a delay of many weeks between the initial procedure and when the transported bone segment ultimately makes contact with the target segment. During that time, the defect interval fills with dense scar and granulation tissue, and the end of the transport segment remodels with rounding of the edges. Revision and bone grafting of the docking site was therefore often performed immediately prior to when contact was achieved. Docking site modification was often undertaken to debride any dense intervening scar and to freshen the osteotomized bone surfaces, and we now consider this part of the standard transport treatment protocol. Contact at the docking site can be optimized and re-alignment of the transported fragment can be performed, if necessary. Augmentation with autologous cancellous bone graft was placed circumferentially, not within the docking site itself. In contradistinction, bone grafting of the docking site following acute shortening was not a planned procedure. However, it may be preferable to routinely use bone graft primarily at the acute shortening docking site in order to augment the probability of union and potentially decrease treatment time. This is a more critical consideration for docking sites involving two diaphyseal bone segments, and may be less important when docking a diaphyseal segment into a metaphyseal bed.

**Statistical Analysis**

All statistical analyses were performed using STATA SE (Version 12.0; StataCorp, College Station, Texas, USA). Means were calculated for continuous variables, and Student’s t-test was used for comparisons between means. Contingency tables (3 x 2) were created, and Fisher’s exact test used to compare bone
results and functional results between both groups. A level of significance of $p < 0.05$ was selected in all analyses, to limit the chance of Type I error to 5%. Effect size and an a-priori sample size was calculated using G*Power 3.1.9.2. (Düsseldorf, Germany) [50]. With $\alpha=0.05$, $\beta=0.8$, df=2 the effect size was calculated to be 0.48. Based on these variables an a-priori sample size calculation was performed and revealed 42 patients were needed to achieve adequate statistical power to limit the risk of Type II error to 5%.

**Results**

A total of forty-two patients with post-traumatic tibial non-unions with bone loss measuring between 3 and 10 cm were included in this study; none were excluded. The tibial bone defect was either secondary to the initial trauma, the result of prior surgery, or a consequence of additional resection at the time of the definitive reconstructive procedure. Group A consisted of twenty-one patients managed by bone transport (Figure 1), and Group B consisted of twenty-one patients managed by acute shortening/lengthening (Figure 2). Most of these cases (36/42) were actively infected at the time of treatment, and the other six cases had a history of deep infection. These two groups were very comparable in all clinically relevant aspects. Complete details of the demographics and clinical characteristics of the study cohort are provided in Table 1. The average bone defect in the transport group measured 7.0 cm, and in the acute shortening group 5.8 cm ($P = 0.05$). The average treatment time in the transport group was 12.5 months (6-23), and in the acute shortening group was 10.1 months (4-18) ($P = 0.02$). Dividing the treatment time by the amount of bone loss yields an external fixation index (EFI) of 1.8 months/cm in the bone transport group, and an EFI of 1.7 months/cm in the acute shortening group ($P = 0.09$). Bone results (radiographic) were slightly better in the acute shortening/lengthening group, but this difference was not significant ($P = 0.23$); functional outcome results were identical ($P = 1$) (Table 2).
Minor complications (resolved without surgery) were 1.2 per patient in the transport group, and 0.5 per patient in the acute shortening group ($P = 0.00001$). Major complications (required additional surgery) in the bone transport group were 1.0 per patient, and 0.4 per patient in the acute shortening group ($P = 0.0003$). Permanent complications (sequelae, unresolved at the end of treatment) were 0.5 per patient in the transport group, and 0.3 per patient in the acute shortening group ($P = 0.28$). Details of the complications in both groups are provided in Table 3.

Eight patients had symptomatic pin site infections in the bone transport group and four patients in the acute shortening group, with multiple wires/pins involved in some patients. These occurred around a wire or pin in a total of 28 out of the 486 inserted (5.8%). Infection signs resolved with local care and systemic administration of antibiotics for 17 of these sites. Exchange of a wire or pin was indicated in 11 cases due to persistent infection; no pin tract infection persisted after removal.

**Discussion**

The most important finding of this study was that the treatment time in external fixation was not significantly different for the acute shortening group (1.7 months/cm) compared to the bone transport group (1.8 months/cm). The between group differences for both bone and functional results were also not significant. The a priori analysis confirms this study was adequately powered to detect any between group differences, if present. When treating infected tibial non-unions with bone defects very similar outcomes were achieved with either bone transport or acute shortening/lengthening. However, the total number of complications per patient was significantly greater in the transport group compared to the acute shortening group. This did not reflect additional procedures related to early bone grafts at the docking site in the bone transport group.

Infected tibial non-unions with segmental bone defects are a formidable challenge, and limb salvage by any technique can be frustrating for both patient and surgeon. Acute
shortening/lengthening and bone transport both employ distraction osteogenesis to regenerate bone loss, and either method facilitates reconstruction and limb salvage. Both can be considered as elements in the spectrum of multi-focal osteosyntheses made possible using the methods of Ilizarov [29,30,32]. The use of external fixation for gradual mechanical distraction [1,4,15,16,31,32,34-37,44-48] has certain advantages, and is an approach that allows for the many elements of pathology to be simultaneously treated in a comprehensive fashion.

Bone transport is an elegant solution for the management of segmental bone loss, but one that often requires patients to spend long periods of time in a circular frame. The main theoretical advantage of acute shortening/lengthening is the early contact across the original area of bone loss, with the expectation of decreased time in external fixation. Immediate docking promotes more rapid union, while compression enhances the mechanical stability of the bone-fixator composite construct. The results of this study demonstrate these two techniques are principally distinguished in the fourth dimension, time. The segmental defect is either eliminated rapidly with acute shortening, or gradually using bone transport. The decision as to which to employ in a given situation is most often dictated by the condition and response of the surrounding soft tissues.

Several publications have compared Ilizarov methods to alternative approaches for the management of segmental tibial bone loss, such as massive cancellous bone grafts [5,15,16]. They have reported comparable clinical results between the two groups, with similar rates of union, eradication of infection, and alignment. However, autologous cancellous bone grafts appear to require more surgical procedures and more transfusions, and bone transport is generally considered a faster, safer, and less expensive strategy [15,16].

Acute shortening for post-traumatic segmental bone loss has already been the subject of several prior publications [5,9-12,36,44-48], including an early paper by Saleh and Rees [36]. They also divided their
patients into two groups comparing bone transport with acute shortening. However, their study cohort was far less homogeneous, including both tibial and femoral cases as well as both circular and unilateral fixators. Their results more clearly favored acute shortening/lengthening relative to bone transport. They concluded that acute shortening/lengthening is simpler than bone transport and required less time to complete, and they recommended using it when possible to close the defect directly. This unfortunately reflects selection bias, considering they initially used bone transport and later introduced acute shortening/lengthening. The subsequent reports by Maini, et al [45], and by Lavini, et al [46] reached similar conclusions, although plagued by some of the same limitations. The study from Mahaluxmivala, et al [47] was better designed, but the sample size was too small to draw any meaningful conclusions.

Most recently, Eralp, et al [48] published their results in a large multi-center retrospective study from Turkey, including 74 patients treated by either bone transport or acute shortening/lengthening. This reflects their aggregate experience over a 15-year period, restricted to cases of chronic tibial osteomyelitis and infected non-unions. The surgical techniques they describe are nearly identical in most respects to those employed in the current study [48]. They again have reported very comparable results for these two treatment alternatives with respect to functional and radiographic outcomes, although they failed to conduct a power analysis to determine if their sample size was large enough to detect a difference if present. However, in their series the external fixation index was significantly greater in the bone transport group, but the complication rates were nearly identical in the two groups. In their opinion acute shortening may provide greater patient satisfaction as a result of the potential reduction in time spent in external fixation [48].

Cases with bone defects exceeding 10 cm are generally treated by bone transport, recognizing the limited ability of soft tissues to tolerate acute shortening of this magnitude. Recognizing the apparent benefits of immediate contact, those cases with bone defects less than 3 cm are most often treated by
acute shortening/lengthening. Most previously published studies do not adequately compare the two techniques to fairly determine the preferred role and indications for each method. We sought a direct comparison of these two techniques for the management of bone loss of intermediate size, when either method may be considered applicable. We therefore focused our investigation on cases with segmental bone defects from 3 to 10 cm in length.

Tibial segmental bone loss generally precludes union, and closing this gap is the first challenge; it can be eliminated either acutely or gradually by either of the methods. The next goal is to achieve union of the two bone ends placed in contact across the original defect, most often referred to as the docking site. In our study group over half the patients had an autogenous cancellous bone graft placed at the level of the docking site in order to promote union. Fourteen of the patients in the bone transport group underwent a docking site revision with bone graft (67%), while eight of the patients in the acute shortening group required an unplanned docking site revision with bone graft (38%). This clearly reflects our preference for routine docking site revision during bone transport, immediately prior to contact following translocation of the transport segment. We have incorporated this into our current transport treatment protocol as a planned second stage, scheduled when the remaining defect measures approximately 1 cm. Routine docking site revision with bone grafting provides the greatest opportunity for the most reliable and rapid union by optimizing bone contact and congruity. Most authors currently recommend routine staged docking site revisions during bone transport [15,16,36,38,39,41,42,51], although this is not unanimous [48,52].

Another significant observation from this study is the high incidence of delayed or non-union of the docking site after acute shortening (38%). Considering the immediate contact and enhanced mechanical stability of the bone-fixator composite, there are obvious theoretical benefits for acute shortening compared to bone transport. Failure to empirically bone graft the acute shortening docking site primarily could explain the virtually identical treatment times for both methods. Based on these
results, it may be preferable to use bone graft primarily at the acute shortening docking site in order to augment the probability of union and potentially decrease treatment time. This is a more critical consideration for docking sites involving two diaphyseal bone segments, and may be less important when docking a diaphyseal segment into a metaphyseal bed. Incorporating this aspect into the standard acute shortening surgical protocol may better distinguish the results following these two treatments.

In this series, the results of acute shortening/lengthening are slightly, but non-significantly, better than bone transport, and the complication rate was reduced. It affords certain advantages compared to bone transport, and should be considered when possible based on soft tissue considerations. It is clearly preferable for smaller defects less than 3 cm in size, but may be considered for defects up to 10 cm. For moderate tibial defects between 3 and 10 cm in size acute shortening/lengthening is more technically demanding than bone transport. However, any acute shortening exceeding 5 cm should be conducted with great care, monitoring the response of the vascular flow distally. Acute shortening from 5 to 10 cm should only be attempted through initial partial shortening as dictated by vascular considerations, with subsequent shortening of the residual defect at 2 mm/day until completely eliminated. The treatment method selected is often dictated by soft tissue constraints, recognizing there are advantages for each method given different clinical presentations.

The principle limitation of this study is that it was conducted retrospectively rather than as a randomized controlled trial, and the chart review process is possibly subject to assessor bias. Bone transport was performed more often early in this series, and acute shortening was used only after the surgeons involved had already become experienced with Ilizarov techniques, resulting in selection bias that may be responsible for the observed between group differences in complication rates. The strength of this study resides in the statistical analysis, which confirms the study was adequately powered and the sample size large enough to limit the risk of Type II error. Therefore, the lack of a
statistically significant difference in many parameters confirms these two techniques can achieve very comparable clinical outcomes.

**Conclusions:**

While both techniques demonstrated excellent results, acute shortening/lengthening demonstrated a lower rate of complications and a slightly better radiographic outcome. Bone grafting of the docking site was often required with both procedures.

**References:**


Figure Legends

**Figure 1** 40-year-old male bicyclist struck by a truck, with massive polytrauma including a closed head injury, an unstable pelvis fracture, and an open fracture of the proximal tibia. This Grade 3B open proximal tibial fracture resulted in a 10.3 cm segmental defect. Because of the severity of his associated injuries, the limb was only treated with a splint and local wound care for the first 3 weeks. It was reconstructed through retrograde bone transport with gradual transposition of bone using a distal corticotomy. This panel features a series of images demonstrating the 8 month process, and the final result two full years later:

a) AP radiograph of the proximal tibia fracture after application of a spanning external fixator;

b) Lateral radiograph of the proximal tibia fracture after application of a spanning external fixator;

c) Due to the severity of his head injury, the open tibial fracture was initially managed with splinting and local debridement only for the first 3 weeks. By day 24 this had now become a neglected fracture, with 10 days or more having passed prior to obtaining soft tissue coverage. Tissues are then more likely to be desiccated or necrotic, biofilm is already established, and these injuries require more aggressive debridement;

d) and e) Intra-operative photographs before and after formal debridement. Attempts were made to preserve the posterior cortex, but as seen in e) it was also involved and necrotic;
f) Intra-operative image demonstrating 8 cm segmental defect that resulted from unavoidable delays in treatment (with an additional 2.3 cm limb length discrepancy);

g) Intra-operative image illustrating wound coverage with medial and lateral gastrocnemius flaps;

h) AP radiograph showing a temporary PMMA spacer used to fill the defect and deliver local antibiotics;

i) Intra-operative image showing mature flap after 4 weeks;

j) Intra-operative image demonstrating removal of the spacer, and application of a circular tensioned wire fixator for retrograde bone transport;

k) and l) AP and lateral radiographs shortly after initiation of bone transport;

m) Clinical photograph during bone transport at 18 weeks;

n) and o) AP and lateral radiographs after the completion of bone transport;

p) and q) Clinical photographs of proximal tibia shortly after removal of the fixator demonstrating completion of 8 cm bone transport in 8 months;

r) Long standing radiograph demonstrating anatomical alignment with a residual 2.3 cm leg discrepancy;

s) AP radiograph of the tibia that confirms solid union proximally and mature regenerate distally 2 years after fixator removal;

t) Clinical photograph illustrating appearance of the limb 2 years after fixator removal.
Figure 2 41-year old woman sustained an open fracture of the distal tibia in a motorbike accident, and was initially treated at a peripheral hospital. She was not referred to a tertiary centre until more than 5 weeks after the injury, with another neglected Grade 3A\textsuperscript{52-53} open fracture. Complete debridement resulted in a 3.7 cm segmental defect, reconstructed through acute shortening distally and gradual lengthening proximally; acutely shortening allowed the wound to be closed primarily, avoiding the need for a free flap. This panel features a series of images demonstrating the 6 month process, and the final result two full years later:

a) Radiograph showing widely displaced open fracture of a distal tibia immediately following the injury;

b) AP radiograph of distal tibia immediately after reduction and splinting;

c) AP radiograph of a distal tibia immediately post-operative after debridement and placement of antibiotic beads at a peripheral hospital;

d) Clinical photograph of a persistent open fracture site 6 weeks later, provisionally stabilized with a spanning fixator;

e) Intra-operative clinical photograph demonstrating necrotic bone at the distal end of the proximal fragment;

f) Intra-operative clinical photograph following resection of the involved necrotic bone;

g) and h) Intra-operative clinical photographs illustrating transverse orientation of the wound that re-approximated without tension after acute shortening, obviating the need for a free flap;

i) and j) Clinical photograph and AP radiograph following acute shortening in a temporary spanning external fixator;
k) Clinical photograph illustrating conversion to an Ilizarov external fixator for reconstruction using the strategy of acute shortening distally and gradual lengthening proximally;

l) AP radiograph immediately following corticotomy and application of the Ilizarov fixator;

m) AP radiograph after initiating distraction through the proximal corticotomy;

n) and o) Lateral radiographs of the distraction gap after 2 months and 4 months, respectively;

p) and q) AP and lateral radiographs demonstrating alignment at 1 year after removal of the fixator;

r) AP radiograph confirming union of bone 24 months after removal;

s) and t) Clinical photographs, lateral and AP, demonstrating cosmesis of limb at 2 years after removal of the fixator.
Table 1: Patient Demographics and study design

<table>
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<th>Acute Shortening (AS)</th>
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<td>Age (years)</td>
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<td>Sex</td>
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<td>Bone Defect (cm)</td>
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<td>Prior Surgeries (per patient)</td>
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Post-Operative Evaluation

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<td>Follow-up (months)</td>
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<td>External Fixation Time (months)</td>
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Table 2: Clinical Outcomes: bone and functional results

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<th></th>
<th>Outcome</th>
<th>Bone Transport (BT)</th>
<th>Acute Shortening (AS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone Results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(p = 0.23)</td>
<td>Excellent</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

| Functional Results    |           |                     |                       |
| (p = 0.99)            | Excellent | 14                  | 14                    |
|                       | Good      | 6                   | 6                     |
|                       | Fair      | 1                   | 1                     |

Bone result outcome criteria: union, infection, alignment, limb length discrepancy (LLD)

Functional result outcome criteria: pain, limp, range of motion (ROM), orthosis, and contracture
<table>
<thead>
<tr>
<th></th>
<th>Bone Transport (BT)</th>
<th>Acute Shortening (AS)</th>
<th>P levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Docking Site Revision</td>
<td>14</td>
<td>8</td>
<td>0.06</td>
</tr>
<tr>
<td>Complications minor</td>
<td>1.2</td>
<td>0.5</td>
<td>0.0003</td>
</tr>
<tr>
<td>(per patient)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complications major</td>
<td>1.0</td>
<td>0.4</td>
<td>0.0003</td>
</tr>
<tr>
<td>(per patient)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sequelae</td>
<td>0.5</td>
<td>0.3</td>
<td>0.27</td>
</tr>
<tr>
<td>(per patient)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Surgeries</td>
<td>3</td>
<td>2</td>
<td>0.0002</td>
</tr>
<tr>
<td>(per patient)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Minor Complications – Non-Operative**

<table>
<thead>
<tr>
<th>Event</th>
<th>BT</th>
<th>AS</th>
<th>P levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST problem at docking site</td>
<td>6</td>
<td>0</td>
<td>0.27</td>
</tr>
<tr>
<td>Docking malalignment</td>
<td>6</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>Regenerate malalignment</td>
<td>4</td>
<td>3</td>
<td>0.67</td>
</tr>
<tr>
<td>Delayed union regenerate</td>
<td>5</td>
<td>4</td>
<td>0.7</td>
</tr>
<tr>
<td>Transient knee flexion contracture</td>
<td>2</td>
<td>1</td>
<td>0.54</td>
</tr>
<tr>
<td>Transient ankle stiffness</td>
<td>3</td>
<td>2</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>Total (%)</strong></td>
<td><strong>26/21 (124%)</strong></td>
<td><strong>10/21 (47%)</strong></td>
<td><strong>0.0001</strong></td>
</tr>
</tbody>
</table>

**Major Complications – Surgical Intervention**

<table>
<thead>
<tr>
<th>Event</th>
<th>BT</th>
<th>AS</th>
<th>P levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin exchange for infection</td>
<td>9</td>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>Re-debridement of resection site</td>
<td>6</td>
<td>2</td>
<td>0.23</td>
</tr>
<tr>
<td>Frame modification UA</td>
<td>5</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>Re-fracture of docking site</td>
<td>1</td>
<td>1</td>
<td>0.47</td>
</tr>
<tr>
<td>Equinus requiring TAL</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Total (%)</strong></td>
<td><strong>22/21 (105%)</strong></td>
<td><strong>8/21 (38%)</strong></td>
<td><strong>0.0003</strong></td>
</tr>
</tbody>
</table>

Table 3: Complications