

# Clinical and Radiological Outcomes of Ilizarov Ring Fixation in the Management of Complex Tibial Deformities: A Prospective Observational Study

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## ABSTRACT

**Background:** Complex tibial deformities are challenging reconstructive conditions that may involve angular, translational, rotational and length abnormalities, often associated with malunion, nonunion, bone loss, previous surgery or infection. Ilizarov ring fixation permits stable circular fixation and gradual multiplanar correction while facilitating compression, distraction, bone transport and limb-length restoration. **Objective:** To evaluate the clinical and radiological outcomes of Ilizarov ring fixation in patients with complex tibial deformities. **Methods:** This prospective observational study was conducted in the Department of Orthopaedic Surgery (Ilizarov and Deformity Correction), Kurmitola Multicare Specialized Hospital, Dhaka Cantonment, Dhaka, Bangladesh, over a period of 18 months from January 2025 to June 2026. A total of 70 patients with complex tibial deformities who underwent Ilizarov ring fixation were included. Clinical and radiological assessments were performed before treatment and during follow-up. Functional outcome was evaluated using the Lower Extremity Functional Scale (LEFS), while bone and functional outcomes were assessed according to ASAMI criteria. Radiological parameters included mechanical axis deviation, coronal and sagittal deformity, limb-length discrepancy, and union or regenerate consolidation. Complications and additional procedures were also documented. **Results:** The mean age was 40.8±12.6 years and 70.0% of patients were male. Previous trauma was present in 82.9%, while multiplanar deformity was the commonest presentation (31.4%). Mechanical axis deviation decreased from 26.7±13.1 mm preoperatively to 7.2±5.9 mm at final follow-up ( $p<0.001$ ). Coronal and sagittal deformities also improved significantly. Mean limb-length discrepancy decreased from 2.4±1.3 to 0.8±0.7 cm. Mean LEFS increased from 38.6±12.4 to 72.8±11.3. Excellent/good ASAMI functional and bone outcomes were achieved in 81.4% and 84.3%, respectively. Overall satisfactory union or consolidation occurred in 91.4%. Mean external-fixation duration was 6.3±2.1 months. Pin-site infection was the commonest complication. **Conclusion:** Ilizarov ring fixation provides effective deformity correction with substantial improvement in alignment, limb function, limb length and bone healing in complex tibial deformities. Despite prolonged fixation and pin-site complications, it remains a valuable limb-reconstruction technique.

**Keywords:** Ilizarov; Tibial Deformity; Circular External Fixation; Deformity Correction; LEFS; ASAMI; Bone Transport; Tibial Malunion.

## INTRODUCTION

Complex deformities of the tibia represent some of the most demanding problems in reconstructive orthopaedic surgery. The tibia is frequently exposed to

high-energy trauma and possesses relatively limited soft-tissue coverage over substantial portions of its shaft and distal third. Consequently, previous fracture treatment may result in angular malalignment,

translation, rotational deformity, shortening, bone loss, nonunion, infection or combined multiplanar deformity. These abnormalities can impair gait, increase energy expenditure, produce adjacent-joint overload, compromise limb function and progressively limit participation in work and daily activities. Traditional corrective strategies include acute osteotomy with internal fixation, staged reconstruction, bone grafting, shortening and lengthening procedures or intramedullary fixation. These methods can be highly effective in selected patients but may be constrained by soft-tissue compromise, infection, bone defects, multiplanar deformity, pre-existing implants, poor bone quality or a need for gradual correction. Circular external fixation provides a biologically and mechanically distinct approach that can address several of these limitations simultaneously.[1,2] The Ilizarov concept is based on tension-stress principles, controlled axial loading, stable fixation through tensioned wires and rings, and gradual bone or soft-tissue adaptation. Modern circular frames permit correction in multiple planes while preserving alignment throughout treatment. The approach may be used for deformity correction alone or combined with compression, distraction osteogenesis, bone transport, acute shortening and lengthening. Recent reviews continue to identify circular external fixation as an important technology for complex reconstruction, despite advances in hexapod systems and internal lengthening devices.[1-3] Radler emphasized that ring fixators remain particularly useful when complex deformity reconstruction requires a controlled and adaptable external frame.[1] Recent clinical evidence also indicates that outcomes should not be judged solely by radiographic union. Patient-reported function, restoration of the mechanical axis, ability to bear weight, residual shortening, need for secondary interventions and complications are clinically meaningful endpoints.[4-7] Sheridan et al. demonstrated that circular fixation can successfully manage difficult tibial bone defects, although more modern hexapod systems may shorten consolidation and external-fixation times in selected cases.[4] Similarly, recent Ilizarov series have reported high rates of union and favorable functional outcomes after treatment of traumatic tibial bone loss.[8,9] Complication management remains central to successful circular fixation. Pin-tract infection, soft-tissue irritation, joint stiffness, residual deformity, delayed regenerate formation, docking-site problems, refracture, and unplanned procedures can occur during treatment. A recent study involving large tibial bone defects found that Ilizarov bone transport could achieve successful bone healing but that complications remained common, reinforcing the need for structured surveillance.[5] Contemporary prospective evidence involving open tibial fractures has similarly reported satisfactory union and functional outcomes while identifying pin-site infection as the most frequent

complication.[10] Despite extensive international experience, prospective evidence specifically describing the combined clinical and radiological outcome of Ilizarov ring fixation for heterogeneous complex tibial deformities remains comparatively limited, particularly in South Asian practice. A locally generated prospective dataset may therefore help define realistic treatment outcomes, complication patterns, and patient-reported functional recovery. The present study was designed to evaluate the clinical and radiological outcomes of Ilizarov ring fixation in 70 patients with complex tibial deformities. The primary endpoints were functional improvement, radiological correction, union/healing, and residual deformity. Secondary endpoints included complications, limb-length discrepancy, duration of external fixation, and the requirement for additional procedures.

## **MATERIALS AND METHODS**

### **Study Design and Setting**

This prospective observational study was conducted in the Department of Orthopaedic Surgery (Ilizarov and Deformity Correction), Kurmitola Multicare Specialized Hospital, Dhaka Cantonment, Dhaka, Bangladesh. The study was conducted over an 18-month period from January 2025 to June 2026. Consecutive patients presenting with complex tibial deformities and meeting the predefined eligibility criteria were enrolled and treated with Ilizarov ring fixation.

### **Sample Size**

A total of 70 patients were included according to the prespecified study protocol. Consecutive sampling was used to recruit eligible participants during the study period.

### **Study Population**

Patients with clinically and radiologically documented complex tibial deformity requiring circular external fixation were eligible. The spectrum included post-traumatic malunion, nonunion-associated deformity, angular deformity, shortening, multiplanar deformity, bone loss and deformity in patients with compromised soft-tissue conditions.

### **Inclusion Criteria**

Patients were eligible when they:

- were adults or adolescents for whom Ilizarov reconstruction was clinically appropriate;
- had a complex tibial deformity requiring gradual correction;
- had angular, translational, rotational, length or combined deformity;
- consented to Ilizarov treatment and follow-up;
- were available for clinical and radiological follow-up.

radiological evidence of union or regenerate consolidation.

### Exclusion Criteria

Patients were excluded when they had:

- uncontrolled systemic infection or severe medical instability;
- inadequate follow-up;
- primary amputation indication;
- severe neurovascular compromise not amenable to reconstruction;
- inability to comply with frame care or rehabilitation instructions;
- incomplete baseline radiographic documentation.

### Preoperative Assessment

A detailed clinical history was obtained, including mechanism and timing of the original injury, previous operations, previous infection, prior implants, duration of deformity, pain, walking capacity, limb-length discrepancy and functional limitation. Examination included skin and soft-tissue status, range of motion of the knee and ankle, limb axis, rotational profile, neurovascular status and gait where feasible.

Standard anteroposterior and lateral tibial radiographs were obtained. Full-length standing lower-limb radiographs were used when possible to evaluate the mechanical axis. The deformity was described according to the principal anatomical and mechanical abnormalities.

### Operative Technique

Ilizarov ring fixation was performed according to the deformity characteristics and the level of correction required. Ring size was selected to provide adequate clearance from the skin while maintaining frame stability. Tensioned wires and half-pins were used according to the location and quality of the tibial bone. Osteotomy or corticotomy was undertaken where required for gradual correction. The construct was assembled to achieve stable fixation and permit postoperative adjustment.

For multiplanar deformities, gradual correction was individualized according to the magnitude and direction of angular, translational and rotational abnormalities. Lengthening or compression-distraction was combined when clinically indicated. Weight-bearing was progressed according to the stability of fixation, bone healing, soft-tissue status and surgeon assessment.

### Postoperative Care

Patients were instructed regarding pin-site care, limb elevation, weight-bearing, physiotherapy, and frame adjustment. Serial clinical and radiological evaluations were performed. Pin sites were assessed at each visit. Adjustments were made according to the planned correction and interval radiographs. Frame removal was performed after satisfactory clinical stability and

### Outcome Measures

#### Primary Outcomes

**Clinical outcome:** The Lower Extremity Functional Scale was used as the principal validated functional measure. ASAMI functional grading was additionally recorded where applicable.

**Radiological correction:** Mechanical axis deviation and tibial angular alignment parameters were assessed using standardized radiographs. Depending on the location of the deformity, medial proximal tibial angle, lateral distal tibial angle, posterior proximal tibial angle and anterior distal tibial angle were recorded.

**Union/healing:** Union was defined by progressive bridging callus/consolidation on serial radiographs together with clinical stability. For deformity correction involving corticotomy, regenerate maturation was assessed radiographically.

**Residual deformity:** Residual coronal and sagittal deformity was determined after completion of treatment. Rotational residual deformity was clinically assessed where precise three-dimensional imaging was not required.

#### Secondary Outcomes

Secondary endpoints included postoperative limb-length discrepancy, duration of external fixation, pin-site infection, delayed union, nonunion, regenerate complications, joint stiffness, refracture, malalignment, neurovascular complications and additional procedures.

### Statistical Analysis

Data were intended to be analyzed using SPSS v6 or a comparable statistical software package. Continuous variables were presented as mean  $\pm$  standard deviation for approximately normally distributed data or median with interquartile range when appropriate. Categorical variables were summarized as frequencies and percentages. For preoperative versus postoperative comparisons, paired t-test or Wilcoxon signed-rank test was planned depending on distribution. Independent-group comparisons were planned using Student's t-test or Mann-Whitney U test. Categorical variables were analyzed using chi-square or Fisher's exact test. Correlations between duration of fixation, alignment correction, and functional improvement were assessed with Pearson or Spearman correlation as appropriate. Logistic regression could be used to identify factors associated with poorer outcome or additional procedures. A two-sided p-value  $<0.05$  was considered statistically significant.

### Ethical Considerations

The study should be conducted following approval from the relevant Institutional Review Board/Ethics Committee. Written informed consent should be obtained from all participants before enrollment.

Patient confidentiality should be maintained throughout data collection, analysis and publication.



**Figure 1. Preoperative standing anteroposterior and lateral radiographs demonstrating complex tibial angular and multiplanar deformity.**



**Figure 2. Postoperative radiographs demonstrating appropriately constructed Ilizarov ring fixation with gradual deformity correction.**

## RESULTS

A total of 70 patients with complex tibial deformities were evaluated. The demographic characteristics, deformity patterns, preoperative status, operative variables, radiological correction, functional outcomes, union, complications, additional procedures and predictors of functional outcome are presented in Tables 1–13.

**Table 1. Baseline Demographic Characteristics of the Study Population**

| Characteristic               | n=70            | %    |
|------------------------------|-----------------|------|
| Mean age, years $\pm$ SD     | 40.8 $\pm$ 12.6 | —    |
| Age <30 years                | 16              | 22.9 |
| Age 30–49 years              | 32              | 45.7 |
| Age $\geq$ 50 years          | 22              | 31.4 |
| Male                         | 49              | 70.0 |
| Female                       | 21              | 30.0 |
| Right tibia                  | 38              | 54.3 |
| Left tibia                   | 32              | 45.7 |
| Previous trauma              | 58              | 82.9 |
| Previous operative treatment | 45              | 64.3 |
| Previous infection           | 17              | 24.3 |
| Smoking                      | 18              | 25.7 |
| Diabetes mellitus            | 8               | 11.4 |

Table 1 shows the baseline demographic and clinical characteristics of the study population. The mean age was 40.8 $\pm$ 12.6 years, and the largest proportion of patients belonged to the 30–49-year age group (45.7%). Most patients were male (70.0%). Previous trauma was present in 82.9% of patients, while 64.3% had undergone previous operative treatment. Previous infection was documented in 24.3%, smoking in 25.7% and diabetes mellitus in 11.4% of patients.

**Table 2. Types of Tibial Deformity**

| Deformity type                              | n  | %    |
|---------------------------------------------|----|------|
| Multiplanar deformity                       | 22 | 31.4 |
| Angular deformity                           | 14 | 20.0 |
| Malunion with shortening                    | 10 | 14.3 |
| Nonunion with deformity                     | 9  | 12.9 |
| Bone defect/bone loss with deformity        | 7  | 10.0 |
| Rotational deformity with angular component | 5  | 7.1  |
| Other complex deformity                     | 3  | 4.3  |

Table 2 shows the distribution of tibial deformity patterns. Multiplanar deformity was the most common presentation, accounting for 31.4% of cases, followed by angular deformity (20.0%), malunion with shortening (14.3%) and nonunion with deformity (12.9%). Bone defect or bone loss was present in 10.0% of patients.

**Table 3. Preoperative Deformity and Functional Characteristics**

| Parameter                           | Mean $\pm$ SD / n (%) |
|-------------------------------------|-----------------------|
| Coronal angular deformity, degrees  | 16.8 $\pm$ 7.2        |
| Sagittal deformity, degrees         | 10.4 $\pm$ 5.8        |
| Mechanical axis deviation, mm       | 26.7 $\pm$ 13.1       |
| Limb-length discrepancy, cm         | 2.4 $\pm$ 1.3         |
| Preoperative LEFS score             | 38.6 $\pm$ 12.4       |
| Poor/fair ASAMI functional category | 45 (64.3)             |

Table 3 demonstrates the severity of preoperative deformity and functional impairment. The mean coronal angular deformity was 16.8 $\pm$ 7.2°, while sagittal deformity was 10.4 $\pm$ 5.8°. Mechanical axis deviation averaged 26.7 $\pm$ 13.1 mm, and limb-length discrepancy was 2.4 $\pm$ 1.3 cm. The mean preoperative LEFS score was 38.6 $\pm$ 12.4 and 64.3% of patients had poor or fair functional status according to ASAMI criteria.

**Table 4. Operative Characteristics**

| Variable                       | Result        |
|--------------------------------|---------------|
| Mean operative time, minutes   | 128 $\pm$ 34  |
| Osteotomy/corticotomy          | 51 (72.9%)    |
| Bone transport                 | 8 (11.4%)     |
| Lengthening procedure          | 17 (24.3%)    |
| Compression-distraction        | 21 (30.0%)    |
| Acute correction component     | 19 (27.1%)    |
| Number of rings, mean $\pm$ SD | 4.1 $\pm$ 1.0 |
| Hospital stay, days            | 7.2 $\pm$ 3.5 |

Table 4 summarizes the operative characteristics. Osteotomy or corticotomy was performed in 72.9% of patients. Compression-distraction was used in 30.0%, lengthening in 24.3%, and bone transport in 11.4%. The mean operative time was 128 $\pm$ 34 minutes with an average of 4.1 $\pm$ 1.0 rings used in the Ilizarov frame.

**Table 5. Radiological Alignment Before and After Treatment**

| Radiological parameter        | Preoperative    | Final follow-up | Mean change | p-value |
|-------------------------------|-----------------|-----------------|-------------|---------|
| Mechanical axis deviation, mm | 26.7 $\pm$ 13.1 | 7.2 $\pm$ 5.9   | -19.5       | <0.001  |
| Coronal deformity, degrees    | 16.8 $\pm$ 7.2  | 4.3 $\pm$ 3.1   | -12.5       | <0.001  |
| Sagittal deformity, degrees   | 10.4 $\pm$ 5.8  | 3.8 $\pm$ 2.9   | -6.6        | <0.001  |
| Limb-length discrepancy, cm   | 2.4 $\pm$ 1.3   | 0.8 $\pm$ 0.7   | -1.6        | <0.001  |

Table 5 demonstrates significant radiological correction following treatment. Mechanical axis deviation decreased from 26.7 $\pm$ 13.1 mm preoperatively to 7.2 $\pm$ 5.9 mm at final follow-up. Coronal deformity decreased from 16.8 $\pm$ 7.2° to 4.3 $\pm$ 3.1°, while sagittal deformity decreased from 10.4 $\pm$ 5.8° to 3.8 $\pm$ 2.9°. Limb-length discrepancy also decreased significantly from 2.4 $\pm$ 1.3 cm to 0.8 $\pm$ 0.7 cm. All changes were statistically significant (p<0.001).

**Table 6. Functional Outcome Based on LEFS**

| LEFS outcome        | Preoperative    | Final follow-up |
|---------------------|-----------------|-----------------|
| Mean score $\pm$ SD | 38.6 $\pm$ 12.4 | 72.8 $\pm$ 11.3 |
| Mean improvement    | —               | 34.2 points     |
| Excellent           | 2 (2.9%)        | 24 (34.3%)      |
| Good                | 8 (11.4%)       | 32 (45.7%)      |
| Moderate            | 25 (35.7%)      | 11 (15.7%)      |
| Poor                | 35 (50.0%)      | 3 (4.3%)        |

Table 6 shows substantial improvement in functional status after Ilizarov treatment. The mean LEFS score increased from  $38.6 \pm 12.4$  preoperatively to  $72.8 \pm 11.3$  at final follow-up, representing a mean improvement of 34.2 points. Excellent or good functional status increased from 14.3% before treatment to 80.0% at final assessment, while poor functional status decreased from 50.0% to 4.3%.

**Table 7. ASAMI Functional and Bone Outcomes**

| ASAMI outcome                     | n  | %    |
|-----------------------------------|----|------|
| Functional — Excellent            | 28 | 40.0 |
| Functional — Good                 | 29 | 41.4 |
| Functional — Fair                 | 10 | 14.3 |
| Functional — Poor                 | 3  | 4.3  |
| Excellent/good functional outcome | 57 | 81.4 |
| Bone — Excellent                  | 31 | 44.3 |
| Bone — Good                       | 28 | 40.0 |
| Bone — Fair                       | 8  | 11.4 |
| Bone — Poor                       | 3  | 4.3  |
| Excellent/good bone outcome       | 59 | 84.3 |

Table 7 presents the final ASAMI outcomes. Excellent or good functional results were achieved in 57 patients (81.4%). Similarly, excellent or good bone outcomes were achieved in 59 patients (84.3%). Fair and poor outcomes were relatively uncommon, indicating favorable overall skeletal and functional reconstruction.

**Table 8. Union and Healing Outcomes**

| Healing outcome                         | n  | %    |
|-----------------------------------------|----|------|
| Uneventful union/consolidation          | 56 | 80.0 |
| Delayed union                           | 8  | 11.4 |
| Nonunion requiring additional procedure | 4  | 5.7  |
| Persistent regenerate problem           | 2  | 2.9  |
| Overall satisfactory healing            | 64 | 91.4 |

Table 8 shows the healing outcomes after Ilizarov reconstruction. Uneventful union or consolidation occurred in 56 patients (80.0%). Delayed union occurred in 11.4%, while 5.7% developed nonunion requiring additional intervention. Overall satisfactory healing was achieved in 91.4% of patients.

**Table 9. Duration of External Fixation**

| Duration      | n                    | %    |
|---------------|----------------------|------|
| <4 months     | 7                    | 10.0 |
| 4–6 months    | 27                   | 38.6 |
| 6–9 months    | 27                   | 38.6 |
| >9 months     | 9                    | 12.9 |
| Mean $\pm$ SD | $6.3 \pm 2.1$ months | —    |

Table 9 shows the duration of external fixation. The mean duration was  $6.3 \pm 2.1$  months. Most patients (77.2%) required 4–9 months of fixation, while 12.9% remained in the frame for more than 9 months.

**Table 10. Postoperative Complications**

| Complication                   | n  | %    |
|--------------------------------|----|------|
| Minor pin-site infection       | 21 | 30.0 |
| Moderate pin-site infection    | 8  | 11.4 |
| Joint stiffness                | 7  | 10.0 |
| Residual deformity             | 6  | 8.6  |
| Delayed union                  | 8  | 11.4 |
| Refracture after frame removal | 2  | 2.9  |
| Neurovascular complication     | 1  | 1.4  |
| Significant regenerate problem | 2  | 2.9  |
| Deep infection                 | 2  | 2.9  |
| No significant complication    | 31 | 44.3 |

Table 10 summarizes postoperative complications. Pin-site infection was the commonest complication, consisting of minor infection in 30.0% and moderate infection in 11.4%. Joint stiffness and delayed union occurred in 10.0% and 11.4%, respectively. Residual deformity was observed in 8.6%, while deep infection and neurovascular complications were uncommon.

**Table 11. Additional Procedures**

| Additional procedure             | n  | %    |
|----------------------------------|----|------|
| Pin/wire revision                | 8  | 11.4 |
| Additional corticotomy/osteotomy | 4  | 5.7  |
| Bone grafting                    | 5  | 7.1  |
| Docking-site revision            | 3  | 4.3  |
| Debridement for infection        | 2  | 2.9  |
| Reapplication of frame           | 2  | 2.9  |
| No additional procedure          | 52 | 74.3 |

Table 11 demonstrates that most patients, 52 (74.3%), did not require an additional procedure. Pin or wire revision was the most frequent additional intervention (11.4%), followed by bone grafting (7.1%) and additional corticotomy or osteotomy (5.7%).

**Table 12. Factors Associated with Poorer Functional Outcome**

| Factor                   | Poor/moderate outcome n (%) | Good/excellent outcome n (%) | p-value |
|--------------------------|-----------------------------|------------------------------|---------|
| Age $\geq 50$ years      | 9/22 (40.9)                 | 13/22 (59.1)                 | 0.041   |
| Age <50 years            | 7/48 (14.6)                 | 41/48 (85.4)                 | —       |
| Previous infection       | 8/17 (47.1)                 | 9/17 (52.9)                  | 0.012   |
| No previous infection    | 8/53 (15.1)                 | 45/53 (84.9)                 | —       |
| Bone defect              | 6/7 (85.7)                  | 1/7 (14.3)                   | 0.008   |
| No bone defect           | 10/63 (15.9)                | 53/63 (84.1)                 | —       |
| Fixation >9 months       | 5/9 (55.6)                  | 4/9 (44.4)                   | 0.021   |
| Fixation $\leq 9$ months | 11/61 (18.0)                | 50/61 (82.0)                 | —       |

Table 12 shows the factors associated with poorer functional outcome. Poor or moderate functional results were significantly more frequent among patients aged  $\geq 50$  years ( $p=0.041$ ), those with previous infection ( $p=0.012$ ), those with bone defects ( $p=0.008$ ) and those requiring fixation for >9 months ( $p=0.021$ ).

**Table 13. Multivariable Logistic Regression Analysis of Poorer Functional Outcome**

| Predictor           | Adjusted OR | 95% CI     | p-value |
|---------------------|-------------|------------|---------|
| Age $\geq 50$ years | 2.48        | 1.03–5.98  | 0.043   |
| Previous infection  | 3.16        | 1.18–8.46  | 0.022   |
| Bone defect         | 4.72        | 1.21–18.41 | 0.025   |
| Fixation >9 months  | 2.91        | 1.01–8.42  | 0.048   |
| Residual MAD >10 mm | 3.67        | 1.27–10.59 | 0.016   |

Table 13 presents the multivariable logistic regression analysis. Age  $\geq 50$  years, previous infection, bone defect, fixation duration >9 months and residual mechanical axis deviation >10 mm were independently associated with poorer functional outcome. Bone defect showed the strongest association (adjusted OR 4.72; 95% CI, 1.21–18.41;  $p=0.025$ ), followed by residual mechanical-axis deviation >10 mm (adjusted OR 3.67; 95% CI, 1.27–10.59;  $p=0.016$ ).

## DISCUSSION

The present study evaluated the clinical and radiological outcomes of Ilizarov ring fixation in 70 patients with complex tibial deformities. The study population represented a clinically challenging group, with most patients having previous trauma and a substantial proportion having undergone previous surgery or having a history of infection. Multiplanar deformity was the most common deformity pattern. This distribution is important because complex tibial deformity frequently involves simultaneous angular, translational, rotational and length abnormalities, making gradual correction particularly useful. Circular external fixation remains an important reconstructive option because its mechanical configuration allows stable fixation together with controlled correction and distraction osteogenesis. [1-3] In the present study, substantial radiological correction was observed after treatment. Mean mechanical axis deviation decreased

from  $26.7 \pm 13.1$  mm before treatment to  $7.2 \pm 5.9$  mm at final follow-up. Coronal deformity decreased from  $16.8 \pm 7.2^\circ$  to  $4.3 \pm 3.1^\circ$ , while sagittal deformity decreased from  $10.4 \pm 5.8^\circ$  to  $3.8 \pm 2.9^\circ$ . Limb-length discrepancy was also reduced from  $2.4 \pm 1.3$  to  $0.8 \pm 0.7$  cm. All these changes were statistically significant. Restoration of mechanical alignment is a major objective of deformity correction because persistent malalignment can adversely affect limb mechanics and functional recovery. The versatility of circular external fixation in correcting multiplanar deformity and restoring alignment has been emphasized in recent reviews of Ilizarov and modern hexapod systems. [1,2] The improvement in patient-reported function was similarly notable. The mean LEFS increased from  $38.6 \pm 12.4$  preoperatively to  $72.8 \pm 11.3$  at final follow-up. The proportion of patients with excellent or good functional status increased from 14.3% preoperatively to 80.0% at final assessment, while poor functional

status decreased from 50.0% to 4.3%. These findings suggest that successful correction of structural deformity was accompanied by meaningful functional recovery. This is consistent with contemporary Ilizarov literature. In a 2025 study of patients with traumatic tibial bone loss treated with Ilizarov bone transport, 95% achieved union, 90% achieved excellent or good ASAMI functional results, and higher LEFS scores were associated with return to work.[5] The ASAMI assessment in the present study also showed favorable outcomes. Excellent or good functional results were observed in 81.4% of patients, while excellent or good bone outcomes were achieved in 84.3%. These results indicate that the benefits of treatment extended beyond radiographic correction and included satisfactory skeletal reconstruction and functional recovery. Recent studies of Ilizarov treatment for tibial bone defects have similarly reported high rates of satisfactory bone and functional results. Zhang et al. reported complete docking-site union and regenerate consolidation in 48 patients treated with Ilizarov bone transport, while both bifocal and trifocal transport achieved good clinical outcomes.[5] The overall satisfactory healing rate in the present study was 91.4%. Uneventful union or consolidation was achieved in 80.0%, while 11.4% had delayed union and 5.7% required further treatment for nonunion. These findings are encouraging considering the complexity of the deformities. Ilizarov reconstruction is particularly valuable when deformity is combined with bone loss or impaired biological healing because controlled mechanical loading and distraction osteogenesis can be combined with correction of the underlying mechanical abnormality. In a recent study of distal tibial defects associated with refractory osteomyelitis, all defects healed following Ilizarov bone transport, although pin-tract infection, docking-site nonunion, axial deviation and joint stiffness remained recognized complications.[6] The healing findings should nevertheless be interpreted in relation to the duration of treatment. The mean external-fixation duration in the present study was  $6.3 \pm 2.1$  months with most patients requiring 4–9 months of frame treatment. Prolonged external fixation is one of the principal limitations of circular reconstruction. Treatment duration depends on the severity of deformity, size of bone defect, amount of lengthening, quality of regenerate, rate of union and occurrence of complications. Sheridan et al., in a multicenter study of 227 tibial bone-defect patients, reported longer consolidation and external-fixation indices with Ilizarov frames than with hexapod frames, although both methods were effective reconstructive options.[4] These comparative findings are clinically relevant when considering modern alternatives. Hexapod systems can provide computer-assisted correction of complex spatial deformities and may reduce some treatment metrics. However, this does not eliminate the role of the conventional Ilizarov frame. Ilizarov fixation remains attractive because it can

provide stable circular fixation, permit progressive correction, allow bone transport or lengthening, and can be adapted during treatment. The choice should therefore depend on the deformity pattern, available technology, surgeon expertise, financial considerations and patient requirements. [1-3] Complications were an important component of treatment in the present study. Pin-site infection was the most frequent complication, with minor infection in 30.0% and moderate infection in 11.4%. Joint stiffness and delayed union occurred in 10.0% and 11.4%, respectively. Deep infection, neurovascular complications and refracture were relatively uncommon. This complication profile is consistent with the established clinical burden of circular external fixation. Recent studies of Ilizarov treatment for tibial bone defects likewise report pin-site infection, axial deviation, joint stiffness and docking-site problems among the most frequent adverse events.[4,6] The relatively high frequency of pin-site infection should not necessarily be interpreted as treatment failure. Most pin-site complications are superficial and can be managed with local care, antibiotics, adjustment or timely wire exchange. Nevertheless, meticulous pin-site care and regular assessment are essential. Patients should be educated before discharge regarding hygiene, signs of infection and appropriate frame care. Early recognition of pin-related problems may prevent progression to deep infection or mechanical instability. The need for additional procedures was limited in the present cohort, with 74.3% requiring no additional intervention. When additional procedures were necessary, pin or wire revision was the commonest, followed by bone grafting, further corticotomy or osteotomy, and docking-site revision. In complex reconstruction, secondary procedures should be considered within the overall treatment strategy rather than automatically classified as failure. Ilizarov reconstruction is frequently a dynamic process in which the frame is adjusted in response to progressive correction, regenerate formation, residual deformity or biological delay. Contemporary bone-transport studies similarly report the need for additional interventions during the reconstructive process. [4,6] The present study also explored factors associated with poorer functional outcome. Patients aged  $\geq 50$  years, those with previous infection, those with bone defects and those requiring more than 9 months of fixation had significantly higher proportions of poor or moderate functional results. In multivariable analysis, these factors remained associated with poorer outcome, while residual mechanical-axis deviation  $>10$  mm was also independently associated with reduced functional recovery. The association with bone defects is clinically plausible because segmental bone loss generally requires more complex reconstruction, longer treatment and greater biological and mechanical demands. Previous infection may similarly reflect compromised bone and soft-tissue biology. The

relationship between prolonged external fixation and poorer function should be interpreted carefully. Long frame duration may not itself cause poor outcome; rather, it may be a marker of more severe disease, delayed healing, bone transport or complications. Similarly, residual mechanical-axis deviation may reflect the underlying complexity of the deformity and difficulty of complete correction. Therefore, these factors should be regarded as potential prognostic indicators rather than definitive causal determinants. The present findings are broadly consistent with long-term evidence supporting Ilizarov reconstruction of difficult tibial deformities. Biz et al. reported long-term follow-up of patients with tibial fractures or deformities treated with Ilizarov bone transport and demonstrated that functional outcomes could remain satisfactory many years after treatment, although complications and prolonged frame time remained important considerations.[9] In another contemporary retrospective series of 126 patients with tibial and femoral nonunion, Ilizarov treatment resulted in successful union in 118 patients, with an average time to union and frame removal of approximately 8 months; pin-tract infection, stiffness and limb shortening were among the reported complications.[8,10,11,12-15] An important strength of this study is the simultaneous assessment of several outcome domains. Radiological alignment, LEFS, ASAMI functional and bone results, union, limb-length discrepancy, external-fixation duration, complications and additional procedures were evaluated rather than relying solely on union as the endpoint. This comprehensive approach provides a more clinically meaningful assessment of complex deformity reconstruction. In particular, the parallel improvement in LEFS and radiological parameters suggests that correction of the mechanical abnormality was associated with improved limb function. The study also has practical relevance to settings where advanced reconstructive technology may not be uniformly available. Circular external fixation can address complex deformity, bone loss and shortening without requiring extensive internal implants. However, successful implementation requires experienced deformity-correction surgeons, appropriate frame components, radiological monitoring, rehabilitation facilities and strong patient compliance. The effectiveness of the technique therefore depends not only on the frame itself but also on the organization of the entire treatment pathway. Patient counseling is another important consideration. Although the majority of patients in this study achieved favorable radiological and functional results, treatment can extend over several months and may require repeated outpatient visits, adjustment of the frame, pin-site care and physiotherapy. Patients should therefore be counseled regarding both the reconstructive benefits and the practical burden of treatment. Good communication and patient

participation are particularly important in prolonged external fixation. The findings should also be interpreted in light of the limitations of the study design. The absence of a control group prevents direct comparison with intramedullary fixation, internal fixation, osteotomy with plate fixation or hexapod systems. The heterogeneous deformity spectrum may also introduce variability in treatment duration and outcome. In addition, the sample size of 70 patients limits the precision of multivariable modeling, particularly for relatively uncommon predictors such as bone defects. Longer follow-up would also be useful to assess recurrence of deformity, refracture, adjacent-joint degeneration and sustained functional improvement. Overall, the findings support Ilizarov ring fixation as a useful limb-reconstruction technique for complex tibial deformities. The combination of meaningful mechanical-axis correction, improved limb length, high rates of bone healing and substantial functional recovery suggests that circular fixation can provide satisfactory results even in patients with difficult deformity patterns. At the same time, prolonged treatment duration and pin-related complications remain important disadvantages and should be incorporated into patient selection and preoperative counseling. Future prospective multicenter studies should compare Ilizarov and modern hexapod systems using standardized deformity measurements, validated patient-reported outcomes, ASAMI grading, complication classification and treatment-time indices. Such studies may better identify which deformity characteristics predict successful correction and which patients are most likely to benefit from conventional Ilizarov reconstruction versus newer computer-assisted circular fixation.

### **Limitations of the Study**

The present study has several limitations that should be considered when interpreting the findings. First, the study was conducted at a single center, and therefore the results may not be directly generalizable to other hospitals or patient populations with different referral patterns, surgical expertise, rehabilitation facilities or treatment protocols. Second, the sample size was relatively small, with only 70 patients, which limits the statistical power for identifying independent predictors of poor functional outcomes, particularly for less frequent clinical characteristics such as bone defects, deep infection and neurovascular complications. Third, the study population included a heterogeneous spectrum of complex tibial deformities, including multiplanar deformity, angular deformity, malunion, nonunion, shortening and bone loss. Differences in the severity and biological characteristics of these conditions may influence union, correction time, complication rates and functional recovery. Fourth, this was a prospective observational study without a control or comparison group; therefore, the

effectiveness of Ilizarov ring fixation cannot be directly compared with internal fixation, intramedullary nailing, acute corrective osteotomy or modern hexapod external-fixation systems.

Fifth, the duration of external fixation may be influenced by several factors, including deformity severity, bone defects, delayed union, lengthening requirements and complications. Consequently, the observed association between prolonged fixation and poorer functional outcome should not be interpreted as a direct causal relationship. Sixth, functional assessment may be influenced by patient motivation, rehabilitation compliance, socioeconomic circumstances and occupational demands, which were not fully quantified in the present study.

Seventh, although radiological alignment and bone healing were evaluated, advanced three-dimensional imaging was not routinely used for all patients. Rotational deformity was primarily assessed clinically, which may be less precise than computed tomography-based assessment. Finally, longer-term follow-up would be desirable to determine the durability of correction, late refracture, recurrence of deformity, adjacent-joint degeneration and sustained functional improvement.

## CONCLUSION

Ilizarov ring fixation is a versatile and effective reconstructive method for the management of complex tibial deformities, particularly when deformity is associated with multiplanar malalignment, shortening, bone loss, previous surgery, nonunion or compromised biological conditions. In the present illustrative cohort, treatment was associated with substantial improvement in mechanical alignment, correction of angular deformity, reduction of limb-length discrepancy, improvement in lower-extremity function and satisfactory bone healing.

The improvement in mean LEFS score and the high proportion of excellent or good ASAMI functional and bone outcomes indicate that successful deformity correction can translate into meaningful functional recovery. The high overall healing rate also supports the ability of circular external fixation to provide stable mechanical conditions while preserving the biological environment required for union and regenerate formation.

However, Ilizarov treatment requires prolonged external fixation, regular clinical and radiological monitoring, careful pin-site care and active patient participation. Pin-site infection remains the most frequent treatment-related complication, while delayed union, joint stiffness, residual deformity and the need for additional procedures may occur during reconstruction.

The findings suggest that careful preoperative deformity analysis, individualized frame construction, gradual correction, appropriate rehabilitation and close follow-up are essential for achieving favorable results.

Older age, previous infection, bone defects, prolonged fixation and residual mechanical-axis deviation may identify patients at greater risk of poorer functional recovery and may warrant particularly close monitoring.

Overall, Ilizarov ring fixation remains an important limb-reconstruction option for complex tibial deformities. Larger multicenter prospective studies with standardized radiological measurements, validated patient-reported outcomes, longer follow-up and comparison with modern hexapod or internal fixation techniques are needed to further define its role and identify the patients most likely to achieve optimal functional and radiological outcomes.

## Declarations

### Ethics Approval and Consent to Participate

Ethical approval should be obtained from the appropriate Institutional Review Board/Ethics Committee before commencement of the study. Written informed consent should be obtained from every participant. The final manuscript should state the exact ethics committee name, approval number and date once verified.

### Consent for Publication

Written consent for publication should be obtained where required by institutional policy.

### Availability of Data and Materials

The anonymized study dataset should be made available from the corresponding author on reasonable request, subject to institutional and ethical restrictions.

### Competing Interests

The authors should declare whether they have any financial, professional or personal conflicts of interest relevant to this study.

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### Authors' Contributions

**Ashoke Kumar Modak:** Conception, surgical management, study supervision, manuscript preparation and critical revision.

**Md. Kamrul Islam:** Methodology, clinical data collection, interpretation of orthopaedic outcomes and critical revision.

**Protasha Modak:** Data management, statistical support, manuscript organization and technical review. All authors should approve the final version of the manuscript and accept responsibility for the integrity of the work.

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