Correction of Tibial Malunion and Nonunion With Six-Axis Analysis Deformity Correction Using the Taylor Spatial Frame

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Objective: To determine the effectiveness of six-axis analysis deformity correction using the Taylor Spatial Frame for the treatment of posttraumatic tibial malunions and nonunions.

Design: Retrospectively reviewed, consecutive series. Mean duration of follow-up was 3.2 years (range 2–4.2 years).

Setting: Tertiary referral center for deformity correction.

Patients/Participants: Eighteen patients were included in the study (11 malunions and 7 nonunions). All deformities were posttraumatic in nature. The mean number of operations before the application of the spatial frame was 2.6 (range 1–6 operations). All patients completed the study.

Intervention: Six-axis analysis deformity correction using the Taylor Spatial Frame (Smith & Nephew, Memphis, TN) was used for correction of posttraumatic tibial malunion or nonunion. Nine patients had bone grafting at the time of frame application. One patient with a tibial plafond fracture simultaneously had deformity correction and an ankle fusion for a mobile atrophic nonunion. Two patients had infected tibial nonunions that were treated with multiple débridements, antibiotic beads, and bone grafting at the time of spatial frame application. A rotational gastrocnemius flap was used to cover a proximal third tibial defect in one patient. The average length of time the spatial frame was worn, time to healing, was 18.5 weeks (range 12–32 weeks).

Main Outcome Measurements: Assessment of deformity correction in six axes, knee and ankle range of motion, incidence of infection, and return to preinjury activities.

Results: Of the 18 patients treated with the Taylor Spatial Frame, with adjunctive bone graft as necessary, 17 achieved union and significant correction of their deformities in six axes (ie, coronal angulation and translation, sagittal angulation and translation, rotation, and shortening). Fifteen patients returned to their preinjury activities at last follow-up.

Conclusion: Six-axis analysis deformity correction using the Taylor Spatial Frame is an effective technique to treat posttraumatic malunions and nonunions of the tibia, with several advantages over previously used devices.

Key Words: malunion, nonunion, spatial frame, deformity

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Small-wire circular fixators and hybrid external fixation techniques for the management of tibial nonunions and malunions have become popular in recent years.[1–3] Indications for these devices include proximal or distal metaphyseal tibial nonunions or malunions, tibial fractures with bone loss, limb shortening, and infected nonunions. These devices have several distinct advantages over other operative techniques, advantages that have been demonstrated classically by the Ilizarov fixator.[4–6]

Despite the generally good results of these devices, the Ilizarov system uses hinge and translation mechanisms that are specifically oriented for a given case and requires sequential correction for multiaxial deformities. Because of the complexity of performing sequential corrections, there is a steep learning curve to using the Ilizarov system for the management of multiaxial deformities; the complication rate has been shown to decrease and the accuracy of correction to increase with surgical experience.[7,8] The Taylor Spatial Frame (TSF) (Smith & Nephew, Memphis, TN) uses the slow correction principles of the Ilizarov system using a six-axis deformity analysis incorporated within a computer program. The aim of our study was to assess the efficacy of treatment of malunion, aseptic and infected nonunion, and shortening after traumatic injuries to the tibia using six-axis deformity analysis and the TSF.

MATERIALS AND METHODS

From January 1998 to January 2001, 18 patients were treated at the NYU–Hospital for Joint Diseases with the TSF for posttraumatic malunion or nonunion of the tibia. There were 11 men and 7 women with a mean age of 29.6 years

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(range 10–64 years). There were 11 malunions and 7 nonunions (including 2 infected nonunions). There were five atrophic nonunions and two hypertrophic nonunions, which were determined on preoperative radiographic evaluation. The mean number of operations before the application of the spatial frame was 2.6 (range 1–6 operations). Seven fractures were originally open injuries: grade II (three), grade IIIA (two), grade IIIB (one), and grade IIIC (one). There were nine malunions in the diaphysis of the tibia, one malunion in the proximal metaphysis, and one malunion in the distal metaphysis. There was one nonunion in the proximal metaphysis of the tibia, three nonunions in the diaphysis, and three nonunions in the distal metaphysis.

Nine patients had autogenous iliac crest bone grafting at the time of frame application. One patient with a tibial plafond fracture simultaneously had deformity correction and an ankle fusion for a mobile atrophic nonunion.

Two patients had an infected tibial nonunion. These infected nonunions were treated with multiple débridements and placement of gentamicin beads. The beads were removed at 6 weeks, and the fractures were bone grafted along with the application of the TSF. A rotation gastrocnemius flap was used to cover the proximal third anteromedial defect in one patient.

The medical records and serial radiographs of all 18 patients were reviewed. A standard physical examination was performed preoperatively and postoperatively for all patients as per protocol. Rotational deformity was measured clinically in the sitting position with the knee and ankle flexed to 90°. Rotational deformity was present in 9 patients. The mean knee range of motion (ROM) was 117° (range 90–140°). Five patients had a preoperative flexion deformity, with a mean of 14° (range 10–20°). The mean ankle ROM was 34° (range 15–55°).

As part of routine preoperative and postoperative protocol, all patients had full-length, standing anteroposterior (with knees pointing directly forward and a ruler present) and lateral radiographs to assess alignment and leg length. Preoperatively, there were 6 patients with mean shortening of the tibia of 6.8 mm (range 5–30 mm). The mean preoperative magnitude of angulation deformity was 22.4° (range 8–66°). The mean preoperative magnitude of translational deformity was 7.9 mm (range 0–40.6 mm). The mean values of the preoperative deformity parameters for our study group are shown in Table 1.

During the correction phase, patients were seen weekly or biweekly. Patients were given a schedule for turning the knobs on the struts, printed out using a computer software program designed for the TSF. All patients were allowed to bear weight as tolerated on the affected extremity. Standard pin care involved showering and application of dry gauze around the pins. The TSF was removed when tricortical consolidation was seen on anteroposterior and lateral radiographs. Before removal, the frame was destabilized slowly by removing 4 struts over a 2-week period.

TABLE 1. Mean Values for Preoperative Deformity Parameters

	Mean (range)	SD
Coronal plane angulation (°)	11.7 (0–24)	6.8
Sagittal plane angulation (°)	10.3 (0–57)	16.1
Angulation magnitude (°)	22.4 (8–66)	14.8
Shortening (mm)	6.8 (5–30)	11.2
Rotation (°) (negative for internal rotation)	0.6 (−15–25)	4.7
Coronal plane translation (mm)	4.9 (0–25)	8.6
Sagittal plane translation (mm)	2.6 (0–20)	5.4
Translation magnitude (mm)	7.9 (0–40.6)	13.1

Deformity correction or compression of a nonunion with the TSF is achieved in conjunction with specialized computer software. The preoperative planning with this fixator requires determining the origin on the reference fragment. A corresponding point is determined on the alternate fragment. One can choose the proximal or distal fragment as the reference fragment. The analysis is performed on the anteroposterior and lateral radiographs. The origin and the corresponding points align after the deformity correction (ie, after reaching final numbers on struts from the computer program). The origin in the TSF concept is on the reference fragment and is the point we wish to correct around. It does not have to be the point of deformity; it simply needs to be the point at which the deformity was defined for the computer program. A simple example would be when one wishes to compress a nonunion. The origin may be a point on the proximal fragment, and the corresponding point would be 5 mm distal to the nonunion on the distal fragment, and therefore the nonunion would compress.[9,10]

We used approximately two finger-breadths' space between the ring and the skin anteriorly to determine the ring size. The neutral frame height (NFH) was chosen based on the limb length and the condition of the skin for the placement of a frame on a stiff deformity (chronic mode) or determined by adding the length of proximal and distal fragments (rings first method). The NFH is the distance between the rings when all the struts are the same length after initial correction. All patients who had mobile nonunions had the ring first method, meaning the rings were placed on the proximal and distal fragments parallel to their respective joints, then struts were attached. This included the five atrophic nonunions.

The proximal ring diameter, distal ring diameter, NFH, and distal or proximal reference fragment constitute the frame parameters. The mounting parameters are determined between the reference ring and the tibia. This describes the position of the tibia within the frame. The parameters include anteroposterior frame offset, lateral frame offset, axial frame offset, and rotary frame offset. These numbers are placed after the reference ring has been placed.

The deformity parameters are placed to preconstruct the frame to match the deformity in a stiff nonunion or malunion. These parameters include anteroposterior angulation, lateral angulation, axial translation (ie, short or long), anteroposterior translation, lateral translation, and rotation.[9–12]

The structure at risk is determined. This is a nerve, artery, skin, or bone that we wish to lengthen or shorten at a specific rate (ie, 1 mm per day). The distance of this structure from the origin is determined, the acceptable rate is entered, and the computer determines the days of correction. We place a start date, then a schedule to completion is created. We brought all patients to NFH, which meant the proximal and distal rings were parallel, then performed a "residual" correction if a deformity persisted. A residual correction is achieved by inputting into the computer that we were in a residual mode and determining new deformity and mounting parameters at that time.[9–12]

RESULTS

Mean follow-up was 3.2 years (range 2–4.2 years). All 18 patients were interviewed and examined. The average length of time the spatial frame was worn, time to healing, was 18.5 weeks (range 12–32 weeks). All patients had gradual correction of their deformity (Figs. 1–6).

The mean values of the deformity parameters for our study group after correction and healing are shown in Table 2. The mean magnitude of angulation deformity after correction and healing was 1.8° (range 0–3.6°). The mean magnitude of translational deformity after correction and healing was 1.3 mm (range 0–3 mm). Rotational deformity was corrected in all patients (Table 2). Using the *t* test for related samples, the preoperative-to-postoperative correction of the six axes deformity was found to be statistically and clinically significant for all of the above-mentioned parameters ($P < 0.001$). Seven patients required correction of residual deformity, perhaps due to loss of stiffness in the wires and/or pins or initial errors in the calculations of the deformity or mounting parameters. This required a new schedule to be given after the rings were parallel (ie, after they reached NFH).

FIGURE 1. Preoperative clinical picture of a 67-year-old man with a posttraumatic deformity of the left lower leg.

FIGURE 2. Anteroposterior radiograph demonstrating a valgus deformity and nonunion of the left distal tibia and fibula fractures.

The mean range of knee motion at latest follow-up was 132° (range 105–150°). Two patients had a fixed knee flexion deformity of 10° and 15°. The mean dorsiflexion at the ankle was 23° (range 15–35°), and the mean plantar flexion was 30° (range 15–45°). The lengths of the tibiae were within 0.4 mm (range −3–3) mm) to that of the normal side.

Three patients developed a superficial pin tract infection. There was no sign of osteomyelitis clinically or radiographically. One patient failed treatment; he had a nonunion whose deformity initially was corrected with the TSF but had premature removal of the frame at 8 months when radiographs showing abundant callus at the nonunion site made distinction with consolidation difficult. One month later, the patient had developed a varus deformity through the healing fracture of his

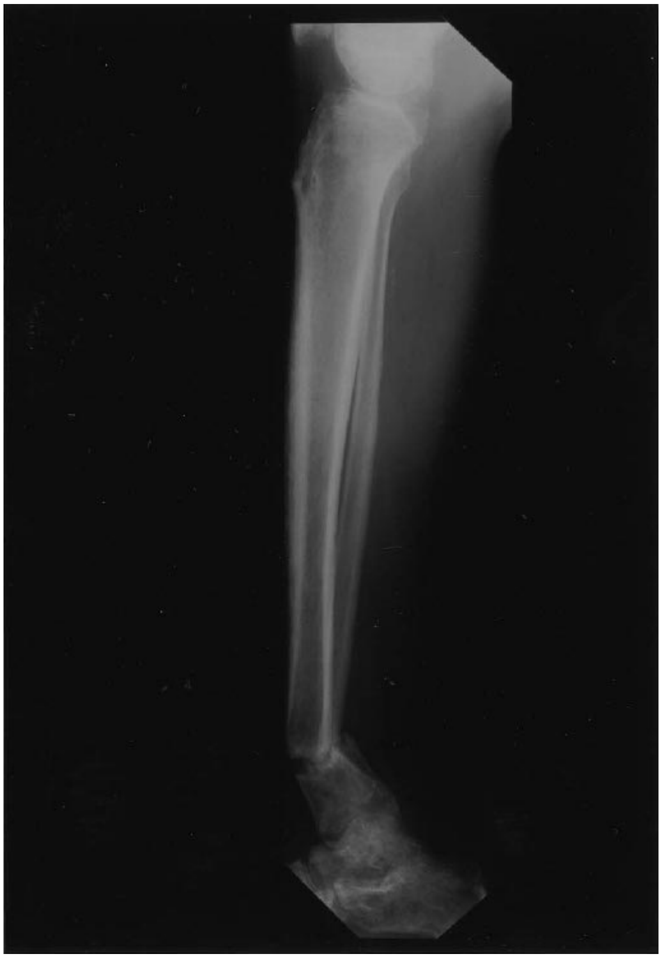

FIGURE 3. Lateral radiograph demonstrating a procurvatum deformity and nonunion of the left distal tibia and fibula fractures.

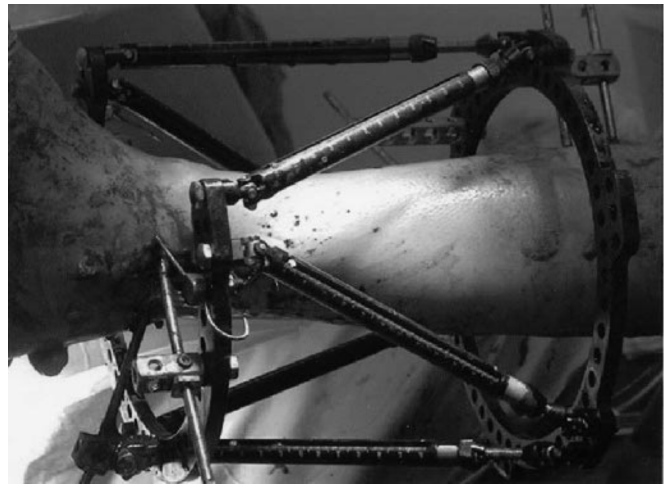

FIGURE 4. Intraoperative picture demonstrating the Taylor Spatial Frame in place.

FIGURE 5. Anteroposterior radiograph demonstrating correction of the valgus deformity and anatomic alignment of a healed distal tibia fracture.

tibia. Fifteen of the 18 patients had returned to their preinjury activities at last follow-up.

DISCUSSION

The management of malunion and nonunion of the tibia is one of the most challenging problems facing the orthopaedic surgeon. Nonunion of the tibia is considered the most frequently observed long bone nonunion; its importance as a weight-bearing bone underlies the need for predictable techniques in its treatment. Reasons for failure of bony healing at the fracture site include the amount of initial fracture displacement, the poor condition of the surrounding soft tissue envelope, and the microvascular compromise at the fracture site. The vascularity of the nonunion (ie, hypertrophic or atrophic) is also a determining factor in bony healing because vascular or hypertrophic nonunions present less of a treatment problem than atrophic nonunions.[13] The common goals of treatment are to correct axial or rotational malalignment, equalize limb

FIGURE 6. Lateral radiograph demonstrating correction of the procurvatum deformity and anatomic alignment of a healed distal tibia fracture.

lengths, prevent or treat established infection, and allow functional restoration of the limb.[14,15]

Generally good results have been seen in the treatment of tibial nonunions with small-wire circular frame devices. Paley et al[16] reported a 100% union rate in 25 patients treated with the Ilizarov fixator for tibial nonunions with segmental bone loss. Ebraheim et al[17] found an 89% union rate in nine patients treated for tibial nonunions with angular deformity. Lonner et al[18] had an 80% union rate in 10 patients treated with the Ilizarov fixator, with complete correction of limb length in five cases and correction of angular and rotational deformity to within 5° in seven cases. Laursen et al[19] reported a 94% union rate in 16 patients treated with the Ilizarov fixator for complex tibial nonunions, with limb-length discrepancy reduced to within 1.5 cm of the contralateral leg.

TABLE 2. Mean Values for Deformity Parameters after Correction and Healing

	Mean (range)	SD
Coronal plane angulation (°)	1.4 (0–3)	1.1
Sagittal plane angulation (°)	0.9 (0–2)	0.8
Angulation magnitude (°)	1.8 (0–3.6)	1.0
Shortening (mm)	0.4 (−3–3)	1.5
Rotation (°) (negative for internal rotation)	0.6 (−3–4)	1.8
Coronal plane translation (mm)	0.8 (0–3)	0.9
Sagittal plane translation (mm)	0.7 (0–2)	0.8
Translation magnitude (mm)	1.3 (0–3)	0.9

The correction of residual deformity is difficult using the Ilizarov system. To correct residual translational and/or rotational deformities with the Ilizarov system, one has to make adjustments after the oblique plane angular deformity is corrected. This leads to a less-desired sequential correction of the deformity. One also may attempt a ring-in-ring construct to correct rotation and angulation simultaneously; however, this makes the osteotomy and application of the ring fixators complex and prone to error. Sanders et al[20] reported ankle pain as a major disability after use of the Ilizarov fixator for tibial nonunion. We did not note this problem with use of the TSF.

We chose the TSF method when it seemed the most advantageous, such as in proximal or distal malunion or nonunion, compromised skin, infection, severe deformities that were not amenable to acute correction, and failed external fixation. Bone grafting was used for the five atrophic nonunions and in two patients with a significant bone defect anteriorly after an open fracture.

Our experience with the TSF demonstrated that we were able to correct oblique plane angulation, translation, and rotation of a given deformity simultaneously by adjusting only strut lengths on a single frame. We were able to correct multiaxial deformities with relative ease, especially with the use of a computer software program that made planning and correction of the deformity straightforward. This was also the experience of other authors who used computer-assisted six axes correction by TSF[11,12] or by a hexapod.[21]

During planning the correction, we identified the structure at risk during the correction and thereby determined the time of distraction. For example, this was achieved by measuring the distance from the correction site to the peroneal nerve in a valgus deformity correction and inputting the value as well as the safe distraction rate of the peroneal nerve into the program. The program determined the distraction schedule at the osteotomy site based on these numbers. All of our patients were able to follow their frame adjustment schedules with ease.

Residual deformity correction was performed in seven of our patients without difficulty. All seven eventually achieved successful correction of these deformities. We found the need for residual correction was higher in larger deformities and higher initially in our series as we worked through the learning curve of the TSF. None of our patients required a return visit to the operating room for correction of residual deformity, as is required with the Ilizarov fixator. Seventeen of the 18 patients treated with the TSF, with adjunctive bone graft as necessary, achieved union and significant correction of all aspects of their deformities (coronal angulation/translation, sagittal angulation/translation, rotation, and shortening). Although the protocol for deformity correction described was the one used for these patients, today we use the "total residual program," which allows us to bypass the NFH. We progress from one strut length to another strut length, correcting the deformity, without first making the rings parallel. This has simplified the process, yet the principles are the same. Based on our results, we conclude that the six-axis analysis deformity correction using the TSF is an effective technique in treating posttraumatic malunions and nonunions of the tibia, with several advantages over previously used devices.

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