Clin Orthop Relat Res
DOI 10.1007/s11999-009-1161-7

CLINICAL RESEARCH

Does the Taylor Spatial Frame Accurately Correct Tibial Deformities?

S. Robert Rozbruch MD, Kira Segal BA, Svetlana Ilizarov MD, Austin T. Fragomen MD, Gabriel Ilizarov MD

Received: 23 March 2009 / Accepted: 27 October 2009

Abstract
Background Optimal leg alignment is the goal of tibial osteotomy. The Taylor Spatial Frame (TSF) and the Ilizarov method enable gradual realignment of angulation and translation in the coronal, sagittal, and axial planes, therefore, the term six-axis correction.
Questions/purposes We asked whether this approach would allow precise correction of tibial deformities.
Methods We retrospectively reviewed 102 patients (122 tibiae) with tibial deformities treated with percutaneous osteotomy and gradual correction with the TSF. The proximal osteotomy group was subdivided into two subgroups to distinguish those with an intentional overcorrection of the mechanical axis deviation (MAD). The minimum followup after frame removal was 10 months (average, 48 months; range, 10–98 months).
Results In the proximal osteotomy group, patients with varus and valgus deformities for whom the goal of alignment was neutral or overcorrection experienced accurate correction of MAD. In the proximal tibia, the medial proximal tibial angle improved from 80° to 89° in patients with a varus deformity and from 96° to 85° in patients with a valgus deformity. In the middle osteotomy group, all patients had less than 5° coronal plane deformity and 15 of 17 patients had less that 5° sagittal plane deformity. In the distal osteotomy group, the lateral distal tibial angle improved from 77° to 86° in patients with a valgus deformity and from 101° to 90° for patients with a varus deformity.
Conclusions Gradual correction of all tibial deformities with the TSF was accurate and with few complications.
Level of Evidence Level IV, therapeutic study. See the Guidelines for Authors for a complete description of levels of evidence.

The institution of one or more of the authors (SRR, SI, ATF) has received fellowship educational funding from Smith and Nephew Inc (Memphis, TN).
Each author certifies that his or her institution has approved the reporting of these cases, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participating in the study was obtained.

S. R. Rozbruch (✉), K. Segal, S. Ilizarov, A. T. Fragomen, G. Ilizarov
Institute for Limb Lengthening and Reconstruction, Limb Lengthening and Deformity Service, Hospital for Special Surgery, Weill Medical College of Cornell University, 535 East 70th Street, New York, NY 10021, USA
e-mail: Rozbruchsr@hss.edu; Srroz@optonline.net

Introduction

The presence of a limb deformity alters the proper transmission of forces across adjacent joints [25, 39]. In the knee [2, 16, 39] and ankle [15], even moderate malalignment (ie, 5°) reportedly initiates or facilitates the progression of osteoarthritis (OA).

Osteotomy of the tibia can reliably correct malalignment and one report suggests it may lead to cartilage regeneration [19]. Achieving overcorrection with a high tibial osteotomy (HTO) is important for achieving long-term success in the treatment of unicompartmental arthrosis [6, 42]. Although the closing wedge osteotomy can be used to correct malalignment, the technique has several limitations [1, 3, 6, 9]. These include the inability to adjust alignment without additional surgery and shortening results from removal of bone segments. The procedure decreases tibial bone stock in the metaphysis, which can lead to ligament laxity and patella baja, and can compromise future viability of a TKA [32, 37]. More recently, the medial opening wedge osteotomy has gained popularity as another option to avoid the complications associated with the closing wedge technique. This technique also requires acute correction and no ability to correct any residual deformity [7, 9].

A percutaneous osteotomy combined with gradual correction using the TSF provides a way to correct a tibial deformity independent of magnitude, complexity, or location. The procedure uses small incisions and minimal soft tissue stripping, and can be used in all zones of the tibia. Without the need for complex frame modifications, the TSF can be used to correct angulation and translation in the coronal, sagittal, and axial planes around a virtual hinge, therefore, the term six-axis correction. The associated web-based software has simplified planning and performance of deformity correction for patients and physicians and has been used to treat all aspects of deformities in the lower extremities. Use of the TSF is associated with few complications [4, 10, 14, 33, 34, 40, 41, 44, 47] and corrects complex tibial deformities in adults and children.

However, published studies [4, 8, 10, 12, 13, 23, 24, 31, 38, 44] on the TSF have been in the form of case reports, have included small numbers of patients, and have combined various bones and etiologies. In addition, the methods of reporting deformity correction and alignment have been variable.

Using a larger series, we therefore asked the following questions regarding the accuracy and outcome of tibial deformity correction: (1) How accurate is the MAD correction at the proximal tibia? (2) How accurate is the medial proximal tibial angle correction (MPTA) and the lateral distal tibial angle (LDTA) correction at the proximal and distal tibia, respectively? (3) How accurate is correction of a tibial diaphyseal deformity? (4) What are the outcomes regarding SF-36 scores, American Academy of Orthopaedic Surgeons (AAOS) lower limb module (LLM) scores, the need for adjacent joint replacement surgery, and complications?

Patients and Methods

We used our osteotomy registry to identify all 102 patients (122 tibias) who underwent a tibial osteotomy surgery for deformity correction using the TSF (Smith and Nephew, Memphis, TN) between 2000 and 2007. Our indications for use of the TSF were uniplanar coronal plane deformity of a magnitude greater than 10°, oblique plane deformity, presence of rotational deformity, or compromised soft tissue envelope. We excluded patients with nonunions, patients who primarily underwent tibial lengthening, and patients who underwent deformity correction with a different method than the TSF. These methods included a monolateral frame for a coronal plane deformity in the proximal tibia less than 10° and intramedullary nailing for a diaphyseal deformity less than 10°. There were 44 females and 58 males with an average age of 39 years (range, 5–72 years). Twenty of the 102 patients had bilateral surgeries. The causes of deformity included 30 posttraumatic malunions and 72 cases of nontraumatic nature, including those of congenital, developmental, and neurologic etiologies. We created three groups by the location of the tibial osteotomy: proximal third (n = 84), middle third (n = 17), and distal third (n = 21). The proximal group was further divided into two subgroups: (1) treatment goal was a MAD of 0 mm (center) or (2) treatment goal was overcorrection of the MAD to 6 to 12 mm medial or lateral depending on the presenting problem. Twenty-three of the 84 limbs were intentionally overcorrected [6, 7]. The patients who had intentional overcorrection had either unicompartmental arthritis or a valgus deformity. The minimum followup after frame removal was 10 months (average, 48 months; range, 10–98 months). No patients were lost to followup. The study reflected a chart review and no patients were recalled specifically for this study. This was an Institutional Review Board-approved retrospective study.

Clinical preoperative evaluation included history and physical examination. Gait was observed. One of us (SRR) measured frontal plane deformity on a 51-inch erect leg bipedal radiograph. If there was a leg-length discrepancy (LLD), blocks (to the nearest 5 mm) were placed under the affected foot to level the pelvis and the height of the blocks was recorded. Leveling the pelvis improves reliability of the measurements of length and alignment on the 51-inch radiograph [36]. LLD was measured on the radiograph. MAD and joint orientation angles, lateral distal femoral angle, MPTA, posterior proximal tibial angle (PPTA), and LDTA were measured using the methods described by Paley et al. [25, 27]. We recorded the magnitude of the deformity by measuring the angle formed by the intersection of a line drawn from the center hip through the knee center with that of the distal mechanical axis of the tibia. In cases in which neutral alignment was the goal, the proximal mechanical axis line was drawn through the center of the knee. When overcorrection was the goal, the proximal mechanical axis line was drawn to the desired location on the knee. The mechanical axis of the opposite lower extremity was not used as the goal. In addition, we routinely obtained AP and lateral view radiographs of the tibia. Ankle deformity was evaluated by radiographs taken with the xray beam centered on the ankle. The outcome includes MAD data points that are medial and lateral to midline. To report the outcome most accurately, we averaged the medial data points and the lateral data points separately. This generates separate medial and lateral values.

All surgeries were performed by the senior author (SRR). Through a 1-cm incision, the tibial osteotomy was performed using a multiple drill-hole technique and it was completed with an osteotome. The location of the osteotomy was at or near the apex of the deformity. When the osteotomy was away from the apex of the deformity, intentional translation at the osteotomy site was needed to correct the limb alignment (Fig. 1) [25, 27]. Osteotomies were complete but left nondisplaced. Fibula osteotomies were performed in all cases. The location of the fibula osteotomy was the middle of the bone when accompanying a proximal or middle tibial osteotomy and was in the distal third when accompanying a distal tibia osteotomy. TSF frames were fixated to the bone with tensioned wires and hydroxyapatite-coated half pins. All corrections were made gradually after a latency phase of 7 to 10 days.

We entered deformity parameters into the TSF web-based software computer program [30, 43] and generated

Fig. 1A–I (**A**) The preoperative front view of a 49-year-old woman with a varus deformity of the tibia is shown. (**B**) The preoperative AP radiograph shows 46° varus. (**C**) The preoperative bipedal 51-inch radiograph shows a MAD of 127 mm medial to midline, MPTA of 40°, and 6.5 cm LLD. (**D**) A front view of the leg after surgery shows the TSF applied to match the deformity. (**E**) A front view obtained 5 months after surgery shows correction of the deformity and LLD. The time of deformity correction was 86 days. (**F**) An AP radiograph obtained 5 months after surgery shows correction of the deformity. There is intentional lateral translation of the diaphysis through the regenerate bone. (**G**) A front view was obtained 3 months after frame removal. The total time wearing the frame was 193 days. (**H**) A bipedal 51-inch radiograph was obtained 3 months after frame removal, the LLD was 1 cm and the MAD was 12 mm lateral to the midline. (**I**) An AP radiograph of the knee 12 months after frame removal shows bony remodeling. MAD = mechanical axis deviation; MPTA = medial proximal tibial angle; LLD = leg-length discrepancy.

an adjustment schedule. The program requires input of deformity, frame, and mounting parameters, and a structure at risk, which determines the rate of correction [30, 43]. The patient is instructed to perform gradual adjustments of the six struts of the TSF three times per day. At the end of the schedule, which typically lasts 2 to 6 weeks, one of us (SRR) determined the limb alignment with physical examination and radiographs. We inspected the patient standing from the front, back, and side views and focused on iliac crest symmetry and leg alignment. On the 51-inch standing radiograph, we measured leg lengths, MAD, and joint orientation angles using the same methods used before surgery. When there was residual deformity, we generated and implemented another correction schedule.

Our criteria for frame removal were time of at least 2.5 months for angular correction and a reasonable external fixation index of 1.5 months per centimeter when lengthening also was performed [13], ability to walk with minimal assistance, and the presence of bridging callus on three of four cortices using the AP and lateral radiographs. The total time wearing the frame averaged 130 days (range, 71–355 days), whereas the frame was used dynamically to correct deformity for 34 days (range, 7–99 days). Patients had an average of two schedules (range, 1–5 schedules), which they followed to turn struts on the TSF. These included the initial schedule and additional residual schedules. The total amount of simultaneous lengthening was an average of 1 cm (range, 0–6.6 cm). Twelve patients underwent simultaneous lengthening greater than 2 cm.

After surgery, patients were allowed to bear weight as tolerated and wean from the crutches as tolerated. For unilateral cases, most patients were walking without the need for two crutches at 6 to 8 weeks after surgery. Knee and ankle ROM exercises were encouraged with supervision of a physical therapist three times per week for 1 hour. Patients also were given a daily 1-hour home therapy program. Patients with bilateral deformities had staged correction with the second-side surgery typically at 6 to 8 weeks after the first side. ROM exercises of the knee and ankle were encouraged. A daily shower, including washing the pin sites with antibacterial soap, was encouraged. This was followed by daily pin care with half-strength hydrogen peroxide and then coverage of pin sites with a dry sterile gauze wrap. Patients were seen in the clinic every 10 to 14 days by the senior author (SRR) during the distraction phase. Once the alignment was corrected and the adjustments ended, patients were seen monthly until frame removal.

Rotational deformity was measured clinically by observing gait, foot progression angle, and thigh-foot axis in the prone position [25]. The rotational deformity corrections were as large as 40° (Table 1). We did not have a cutoff level for inclusion.

Preoperatively and at the last visit, we obtained SF-36 Health Survey scores (physical function, role physical, bodily pain, general health, vitality, social functioning, role emotional, mental health) [35] and the AAOS LLM Patient Health Outcome Score [34]. SF-36 health surveys and LLM module scores were completed for 55 and 54 of 102 patients, respectively.

We recorded time wearing the frame, number of schedules, complications, and knee and ankle ROM. For all patients, deformity parameters, including degree of varus, valgus, apex anterior and posterior deformity, and internal and external rotation deformity, were extracted from the first schedule. This illustrated the magnitude and nature of the preoperative deformity (Table 1). Alignment of the proximal, middle, and distal tibial osteotomy groups were evaluated separately using the best measurements for each group. To assess alignment of the proximal tibia, MAD, MPTA, and PPTA were measured preoperatively and postoperatively by the senior author (SRR), and intraclass correlation coefficients were determined to test intraobserver reliability. The mean intraobserver reliability for these three measurements was 0.97 (range, 0.82–0.99). We analyzed the outcomes of MAD according to the preoperative treatment goal (normal versus overcorrection). To assess alignment of the middle tibia, we measured an absolute angular value obtained by the intersection of the proximal and distal diaphyseal lines [25, 30]. Whereas the MAD and MPTA are affected most by a proximal tibial deformity and the LDTA is affected most by a distal tibial deformity, these joint orientation angles are not a sensitive measure of a middle tibial deformity. The middle tibial deformity parameters instead were extracted from what was input into the first computer program (middle row of Table 1) and compared with the amount of angular

Table 1. Taylor Spatial Frame deformity parameters for the entire cohort (degrees)

Osteotomy location	Varus	Valgus	Apex anterior	Apex posterior	Internal rotation	External rotation
Proximal tibia	13 (4–46)	13 (4–30)	11 (4–35)	10 (5–20)	15 (10–40)	14 (5–25)
Middle tibia	11 (7–30)	18 (10–37)	11 (4–35)	14 (7–23)	18 (10–35)	13 (5–20)
Distal tibia	12 (5–25)	17 (12–30)	9 (2–22)	10 (4–17)	5 (5)	18 (10–30)

Ranges shown in parentheses.

deformity present on the latest AP and lateral radiographs. To assess alignment of the distal tibia, we measured preoperative and postoperative LDTA.

The aims of the analysis were to confirm a clinically important improvement in certain measurements postoperatively at an average of 48 months as compared with the preoperative measurements. The measurements of clinical importance are MAD in the proximal group, MPTA in the proximal group, LDTA in the distal group, SF-36 health survey scores, and AAOS LLM scores.

The data set of cases was transferred to Systat v10.2 (Systat Software Inc, Richmond, CA). Descriptive statistics were run on all the variables, means and standard deviations, and percentiles. Because differences between two continuous measurements on the same joints were the results of interest, paired t-tests were used. We determined the differences between the preoperative measurement and the corresponding matched postoperative measurement (the difference with time for each patient). No difference or change would result in a mean of zero. The paired t-test was used for each measurement: (1) MAD in the proximal group; (2) MPTA in the proximal group; (3) LDTA in the distal group; (4) SF-36 health survey scores; and (5) AAOS LLM scores.

Results

In the proximal group, the MAD correction was accurate. Patients with a varus deformity had a preoperative MAD of 38 mm medial to the midline. For patients with a goal of a MAD of 0, this improved to an average of 5 mm medial and 5 mm lateral to midline. In patients in whom the goal was overcorrection, the MAD improved to 8 mm lateral to the midline. In the proximal group, patients with a valgus deformity had a preoperative MAD of 33 mm lateral to the midline. For patients with a goal of a MAD of 0, this improved to an average of 8 mm medial and 3 mm lateral to midline. In patients in whom the goal was overcorrection, the MAD improved to 12 mm medial to the midline (Table 2). Sagittal (apex anterior and apex posterior) and axial planes (internal and external rotation) were corrected to a satisfactory degree in all cases.

The corrections of MPTA and LDTA were accurate. In the proximal group, the MPTA improved from 80° to 89° in patients with a varus deformity, and from 96° to 85° in patients with a valgus deformity (Table 3). In the distal group, the LDTA improved from 77° to 86° in patients with a valgus deformity, and from 101° to 90° for patients with a varus deformity (Table 4).

Table 2. Preoperative versus postoperative MAD for the proximal group (mm)

Preoperative deformity and p value	Preoperative MAD	Postoperative goal 0		Postoperative goal overcorrection	
		Medial	Lateral	Medial	Lateral
MAD medial (varus)	38 (1–155)	5 (0–35)	5 (2–10)	—	8 (0–17)
p Value		< 0.001	0.03		0.004
MAD lateral (valgus)	33 (4–83)	8 (4–14)	3 (0–9)	12 (4–29)	—
p Value		0.01	0.05	0.1	

Ranges shown in parentheses; MAD = mechanical axis deviation.

Table 3. Preoperative versus postoperative MPTA for the proximal group (degrees)

Preoperative deformity	Preoperative MPTA	Postoperative MPTA	p Value
Preoperative MPTA less than 90 (varus)	80 (40–89)	89 (80–97)	< 0.001
Preoperative MPTA 90 or greater (valgus)	96 (90–123)	85 (74–101)	0.001

Ranges shown in parentheses; MPTA = medial proximal tibial angle.

Table 4. Preoperative versus postoperative LDTA for the distal group (degrees)

Preoperative deformity	Preoperative LDTA	Postoperative LDTA	p Value
Preoperative LDTA less than 90 (valgus)	77 (75–79)	86 (82–88)	0.4
Preoperative LDTA 90 or greater (varus)	101 (90–111)	90 (90–92)	0.09

Ranges shown in parentheses; LDTA = lateral distal tibial angle.

Table 5. Preoperative versus postoperative SF-36 Health Survey scores

Time and p value	Physical functioning	Role physical	Bodily pain	General health	Vitality	Social functioning	Role emotional	Mental health
Preoperative	47 (0–100)	39 (0–100)	47 (10–100)	74 (20–100)	52 (10–90)	62 (0–100)	67 (0–100)	68 (16–100)
Postoperative	66 (10–100)	65 (0–100)	66 (0–100)	75 (22–100)	62 (5–100)	78 (0–100)	79 (0–100)	79 (40–100)
p Value	< 0.001	0.002	< 0.001	0.6	0.06	0.005	0.8	0.007

Ranges shown in parentheses.

Table 6. Preoperative versus postoperative knee and ankle ROM (degrees)

Time/p value	Knee ROM		Ankle ROM	
	Extension	Flexion	Dorsiflexion	Plantar flexion
Preoperative	0 (−30 to 20)	126 (60–140)	10 (−30 to 30)	40 (20–70)
Postoperative	0 (−10 to 10)	125 (70–145)	11 (0–30)	38 (0–70)
p Value	0.54	1.00	0.70	0.10

ROM = range of motion; ranges in parentheses.

The correction of tibial diaphyseal deformity was accurate. The preoperative middle tibial deformity was multiplanar (Table 1, row 2). Postoperatively, all patients had less than 5° of coronal plane deformity and 15 of 17 patients had less that 5° of sagittal plane deformity. All rotational deformities were corrected.

The SF-36 Health Survey scores improved in all categories (Table 5). LLM scores improved from 76 (range, 5–100) to 86 (range, 51–100) ($p < 0.001$). There were no differences between preoperative and postoperative ankle and knee ROM (Table 6). There were six complications. According to the complication classification described by Paley [26], there were three complications that resolved without surgery, two complications that required operative intervention, and one major complication. Two patients had cellulitis develop that required a 10-day course of intravenous antibiotics. One patient (a man who had breast cancer and was being treated with tamoxifen) had delayed union and lost some of the correction after frame removal. His preoperative MAD was 68 mm medial and he underwent correction to neutral, but after frame removal, he had partial recurrence of the deformity and his final MAD was 35 mm medial (Table 2, row 1). He elected not to have additional surgery. Two patients (three legs) had peroneal nerve neurapraxia that resolved by slowing the correction in one patient and with bilateral nerve release in one patient. These patients had scar tissue from previous surgery. Most patients had superficial pin infections at some point during the treatment that successfully responded to oral antibiotics. There were no deep infections. The goals of surgery were achieved in 121 of 122 limbs (99%). The TSF was used to correct all aspects of a tibial deformity. At the time of review, none of the patients had undergone conversion surgery to TKA, unicompartmental knee arthroplasty, total ankle arthroplasty, or had ankle fusion.

Discussion

Although deformity correction of the tibia often can be accomplished with an acute correction and the use of internal fixation, this method has limitations [1, 28, 42]. The presence of poor skin, multiplanar deformity, history of infection and shortening, and lack of postoperative adjustability shows the limitations of this method. The Ilizarov method using the TSF offers a versatile approach to correct all aspects of a tibial deformity. We therefore asked: (1) How accurate is the MAD correction at the proximal tibia? (2) How accurate are the MPTA and LDTA corrections at the proximal and distal tibia, respectively? (3) How accurate is the correction of tibial diaphyseal deformity? (4) What are the outcomes regarding SF-36 scores, AAOS LLM scores, need for adjacent joint replacement surgery, and complications?

Our study has several limitations. First, the patients were reviewed retrospectively and all data were retrieved from charts. Most of the radiographic measurements were recorded in the chart, but there were times that we needed to measure radiographs retrospectively. However, the measurements were made by one author using a uniform method and our intraobserver reliability was high (0.97). Second, complete sets of the SF-36 and AAOS LLM scores were available for approximately 50% of patients. This may reflect bias and must be taken into consideration. Third, we combined all regions of the tibia in this study, although each region of the tibia has its own

Table 7. Literature summary on Taylor Spatial Frame (TSF) for deformity correction

Study	Population	Design	Anatomic region	Deformity correction	Conclusions regarding TSF
Eidelman et al. [8]	30 children and adolescents	Retrospective	Mixed bones	30/31 anatomically corrected	Accurate fixator for deformity correction
Feldman et al. [12]	18 adults 11 malunions 7 nonunions	Retrospective	Tibia	17/18 achieved significant deformity correction and union	Effective technique for deformity correction
Feldman et al. [10]	19 children and adolescents (22 tibias)	Retrospective	Tibia vara (proximal)	21/22 corrected to within 3°	Accurate and safe correction
Feldman et al. [11]	18 children and adolescents	Retrospective comparison of gradual correction using TSF (18) with acute correction using EBI frame (14)	Tibia vara (proximal)	MAD was 3.1 mm in gradual correction group compared with 17.1 mm in acute correction group. MPTA within 3° of normal in 17/18	Gradual correction with TSF is more accurate than acute correction with EBI frame
Fragomen et al. [14]		Technique article	Proximal tibia		
Naqui et al. [23]	53 children and adolescents (55 limbs)	Retrospective	Tibia (44) Femur (11)	52/55 limbs ended with $<$ 15 mm LLD and 5° angular deformity.	Effective and efficient way to correct a wide variety of simple and complex deformities
Nho et al. [24]		Case report	Tibia	Intentional deformity was temporarily implemented to facilitate wound healing. Deformity correction, lengthening, and union subsequently were achieved	TSF can be used in a versatile fashion to temporarily create and then correct tibial deformity
Rozbruch et al. [30]		Technique article	Tibia		
Siapkara et al. [40]	3 adolescents with anterior growth arrest and recurvatum deformity	Case series	Proximal tibia	PPTA and coronal plane deformity were corrected to normal. LLD was corrected	TSF was used successfully to correct deformity and LLD.
Tellisi et al. [44]	2 adults with congenital limb deficiencies	Case series	Proximal tibia	One patient with varus and shortening had correction to neutral and lengthening; the second patient with valgus had correction to neutral	TSF can be used to correct deformity and lengthen a residual limb to improve prosthesis fit and function
Tsaridis et al. [45]	One patient with Paget's disease	Case report	Proximal tibia	Severe tibial deformity was corrected before a staged TKA	TSF used to correct deformity in Paget's disease.
Wantanabe et al. [47]	One patient with failed opening wedge HTO	Case report	Proximal tibia	Deformity was corrected	TSF successfully used for revision HTO after failed opening wedge correction
Current study	102 adults and children (122 tibia) with complex deformities	Retrospective	Tibia (all zones)	MAD was 3 mm lateral to 8 mm medial after neutral correction; after intentional overcorrection, MAD was 8 mm lateral to 12 mm medial. MPTA improved to 85°–89°. LDTA improved to 86°–89°; 15/17 had less than 5° diaphyseal deformity	Gradual correction with TSF of all tibial deformities is safe and precise

MAD = mechanical axis deviation; MPTA = medial proximal tibial angle; PPTA = posterior proximal tibial angle; HTO = high tibial osteotomy; LDTA = lateral distal tibial angle; LLD = leg-length discrepancy.

measurements. However we thought it was important to consolidate these into one group of tibial deformity to illustrate the comprehensive nature of this approach. We did use different and the most relevant radiographic measurements [25, 27, 36] for proximal, middle, and distal groups, and we evaluated the groups separately for alignment (Tables 2–4) [12, 17, 31, 34, 41, 43].

The TSF has been used for fracture treatment [4] and reconstruction of the tibia [8, 10, 11, 14, 23, 24, 28, 40, 44, 45, 47], ankle [22], femur [8, 21, 29], and upper extremity [38] in children and adults. Precise deformity correction and ease of use have been cited as advantages of the TSF [20, 23, 49].

Gradual correction [11, 44, 45] was done [17, 18]. Patients had an average of two schedules (range, 1–5), which they followed to turn struts on the TSF. The total time wearing the frame averaged 130 days. Although this patient group included only those with deformities, there was associated LLD in some patients (1 cm average; range, 0–6.6 cm). The average final LLD was 0.3 cm (range, 0–5 cm). This explains the long distraction time and time wearing the frame for some patients. Patients who underwent deformity correction without lengthening typically wore the frame for 3 months.

Our outcomes were similar to those in other studies of the TSF [8, 10–12, 14, 23, 24, 30, 40, 44, 45, 47], but our analysis of deformity correction was more detailed (Table 7). In the proximal tibia, the goal of correction is often variable and for this reason, we divided the groups into a neutral goal and a goal of overcorrection. MAD outcome data points are either medial or lateral to the midline, and we reported MAD lateral and medial to the midline separately. All medial MAD data points were averaged and the range was recorded. All lateral MAD data points were averaged and the range was recorded. This results in two separate averages. These were not combined (with a positive and negative value) because in doing so, the mean would be erroneously close to zero despite even a large range. The other option of using an absolute value for MAD and ignoring whether it was medial or lateral was not used in this study. The absolute value method gives less precise outcome information because medial and lateral data points are combined and only a generic distance from the midline is generated. Similarly, MPTA and LDTA were analyzed separately in two groups, less than 90° and 90°or greater [1, 5, 37, 46, 48]. We wanted to determine the accuracy of MAD correction of the proximal tibia. Only one study [11] examined MAD correction by comparing acute and gradual corrections at a proximal osteotomy. Our results were comparable to their outcome of 3.1 mm. However we looked at goals of neutral and overcorrection.

Another goal of our study was to examine the accuracy of joint orientation angle (MPTA and LDTA) correction. The study by Feldman et al. [11] is the only one that examined MPTA correction. They reported correction to within 3° of normal in 17 of 18 patients. Our outcomes were comparable. We observed correction of MPTA in varus and valgus deformities of the proximal tibia in 84 cases.

Table 8. Literature on tibial deformity correction with external fixation (not Taylor Spatial Frame)

Study	Population	Design	Anatomic region	Outcome	Conclusion
Adili et al. [1]	30 adults undergoing HTO	Comparison between closing wedge and using Ilizarov	Proximal tibia	Ilizarov group had better decrease in pain, satisfaction, and function.	Both procedures produce comparable outcomes
Catagni et al. [5]	HTO for medial compartment OA	Technique article	Proximal tibia		HTO with Ilizarov is quick, simple, safe, and effective
Sen et al. [37]	53 adults undergoing HTO for medial compartment OA	Retrospective comparison between IF and Ilizarov frame	Proximal tibia	Ilizarov group had better HSS knee scores, alignment, and prevention of OA progression	Ilizarov frame is good for obtaining precise alignment and has advantages over IF method
Tsumaki et al. [46]	21 patients undergoing bilateral HTO for medial compartment OA with monolateral frame and hemicallotasis	Comparison of bone healing between 2 sides (one treated with ultrasound)	Proximal tibia	Bone mineral density was greater in ultrasound group in 18/21 patients	Ultrasound accelerates callus maturation after open wedge HTO by hemicallotasis
Weale et al. [48]	65 patients (76 tibia) undergoing HTO for medial compartment OA with Ilizarov	Retrospective review	Proximal tibia	Survivorship was 89% and 63% at 5 and 10 years.	Ilizarov outcomes are comparable or better than other techniques; subsequent TKA was straightforward

HTO = high tibial osteotomy; OA = osteoarthritis; HSS = Hospital for Special Surgery; IF = internal fixation.

We did not find a study that examined correction of the LDTA in the distal tibia.

The accuracy of diaphyseal tibial deformity correction was examined. Less than 5° of deformity was achieved in almost all cases. This was comparable to the accuracy of deformity correction reported in other studies [4, 12, 34], but details specifically regarding a middle diaphyseal deformity of the tibia were scant.

Finally, reporting outcomes of our group regarding SF-36 scores, LLM scores, need for joint replacement surgery, and complications was a goal. We did not find other studies that examined SF-36 or LLM scores. Our complications were comparable to those experienced by others [4, 10–12, 21, 37, 48]. None of the TSF studies reported on patients undergoing subsequent joint replacement. Tibial deformity correction with the Ilizarov method not using the TSF also has been used with success (Table 8) [1, 5, 37, 46, 48]. Survivorship rates after a HTO for a medial compartment OA using an Ilizarov frame reportedly are 89% and 63% at 5 and 10 years, respectively [48]. Although we did not have any patients who went on to have a joint replacement, our followup was relatively short (48 months).

Our experience suggests one can comprehensively approach the spectrum of tibial deformities with the TSF. This is particularly useful when there is a history of infection, LLD, and a poor soft tissue envelope.

Acknowledgments We thank Margaret G. E. Peterson, PhD, for assistance with statistical analysis.

References

1. Adili A, Bhandari M, Giffin R, Whately C, Kwok DC. Valgus high tibial osteotomy: comparison between an Ilizarov and a Coventry wedge technique for the treatment of medial compartment osteoarthritis of the knee. *Knee Surg Sports Traumatol Arthrosc.* 2002;10:169–176.
2. Ahlbäck S. Osteoarthrosis of the knee: a radiographic investigation. *Acta Radiol Diagn (Stockh).* 1968;Suppl 277:7–72.
3. Akizuki S, Shibakawa A, Takizawa T, Yamazaki I, Horiuchi H. The long-term outcome of high tibial osteotomy: a ten- to 20-year follow-up. *J Bone Joint Surg Br.* 2008;90:592–596.
4. Al-Sayyad MJ. Taylor Spatial Frame in the treatment of pediatric and adolescent tibial shaft fractures. *J Pediatr Orthop.* 2006;26:164–170.
5. Catagni MA, Guerreschi F, Ahmad TS, Cattaneo R. Treatment of genu varum in medial compartment osteoarthritis of the knee using the Ilizarov method. *Orthop Clin North Am.* 1994;25:509–514.
6. Coventry MB, Ilstrup DM, Wallrichs SL. Proximal tibial osteotomy: a critical long-term study of eighty-seven cases. *J Bone Joint Surg Am.* 1993;75:196–201.
7. Deirmengian CA, Lonner JH. What's new in adult reconstructive knee surgery. *J Bone Joint Surg Am.* 2008;90:2556–2565.
8. Eidelman M, Bialik V, Katzman A. Correction of deformities in children using the Taylor spatial frame. *J Pediatr Orthop B.* 2006;15:387–395.
9. El-Azab H, Halawa A, Anetzberger H, Imhoff AB, Hinterwimmer S. The effect of closed- and open-wedge high tibial osteotomy on tibial slope: a retrospective radiological review of 120 cases. *J Bone Joint Surg Br.* 2008;90:1193–1197.
10. Feldman DS, Madan SS, Koval KJ, van Bosse HJ, Bazzi J, Lehman WB. Correction of tibia vara with six-axis deformity analysis and the Taylor Spatial Frame. *J Pediatr Orthop.* 2003;23:387–391.
11. Feldman DS, Madan SS, Ruchelsman DE, Sala DA, Lehman WB. Accuracy of correction of tibia vara: acute versus gradual correction. *J Pediatr Orthop.* 2006;26:794–798.
12. Feldman DS, Shin SS, Madan S, Koval KJ. Correction of tibial malunion and nonunion with six-axis analysis deformity correction using the Taylor Spatial Frame. *J Orthop Trauma.* 2003;17:549–554.
13. Fischgrund J, Paley D, Suter C. Variables affecting time to bone healing during limb lengthening. *Clin Orthop Relat Res.* 1994;301:31–37.
14. Fragomen A, Ilizarov S, Blyakher A, Rozbruch SR. Proximal tibial osteotomy for medial compartment osteoarthritis of the knee using the Taylor Spatial Frame. *Techn Knee Surg.* 2005;4:175–183.
15. Graehl PM, Hersh MR, Heckman JD. Supramalleolar osteotomy for the treatment of symptomatic tibial malunion. *J Orthop Trauma.* 1987;1:281–292.
16. Hochberg MC, Altman RD, Brandt KD, Clark BM, Dieppe PA, Griffin MR, Moskowitz RW, Schnitzer TJ. Guidelines for the medical management of osteoarthritis: Part II. Osteoarthritis of the knee. American College of Rheumatology. *Arthritis Rheum.* 1995;38:1541–1546.
17. Ilizarov GA. Clinical application of the tension-stress effect for limb lengthening. *Clin Orthop Relat Res.* 1990;250:8–26.
18. Ilizarov GA. *Transosseous Osteosynthesis*. Ed 1. Berlin, Germany: Springer-Verlag; 1992.
19. Koshino T, Wada S, Ara Y, Saito T. Regeneration of degenerated articular cartilage after high tibial valgus osteotomy for medial compartmental osteoarthritis of the knee. *Knee.* 2003;10:229–236.
20. Kristiansen LP, Steen H, Reikeras O. No difference in tibial lengthening index by use of Taylor spatial frame or Ilizarov external fixator. *Acta Orthop.* 2006;77:772–777.
21. Marangoz S, Feldman DS, Sala DA, Hyman JE, Vitale MG. Femoral deformity correction in children and young adults using Taylor Spatial Frame. *Clin Orthop Relat Res.* 2008;466:3018–3024.
22. Matsubara H, Tsuchiya H, Takato K, Tomita K. Correction of ankle ankylosis with deformity using the Taylor Spatial Frame: a report of three cases. *Foot Ankle Int.* 2007;28:1290–1294.
23. Naqui SZ, Thiryayi W, Foster A, Tselentakis G, Evans M, Day JB. Correction of simple and complex pediatric deformities using the Taylor-Spatial Frame. *J Pediatr Orthop.* 2008;28:640–647.
24. Nho SJ, Helfet DL, Rozbruch SR. Temporary intentional leg shortening and deformation to facilitate wound closure using the Ilizarov/Taylor spatial frame. *J Orthop Trauma.* 2006;20:419–424.
25. Paley D. Problems, obstacles, and complications of limb lengthening by the Ilizarov technique. *Clin Orthop Relat Res.* 1990;250:81–104.
26. Paley D. *Principles of Deformity Correction.* Ed 1. Berlin, Germany: Springer-Verlag; 2005.
27. Paley D, Herzenberg JE, Tetsworth K, McKie J, Bhave A. Deformity planning for frontal and sagittal plane corrective osteotomies. *Orthop Clin North Am.* 1994;25:425–465.
28. Pugh K, Rozbruch SR. Nonunions and malunions. In: Baumgaertner MR, Tornetta P, eds. *Orthopaedic Knowledge Update Trauma 3.* Rosemont, IL: American Academy of Orthopaedic Surgeons; 2005:115–130.
29. Rogers MJ, McFadyen I, Livingstone JA, Monsell F, Jackson M, Atkins RM. Computer hexapod assisted orthopaedic surgery

(CHAOS) in the correction of long bone fracture and deformity. *J Orthop Trauma.* 2007;21:337–342.
30. Rozbruch SR, Fragomen AT, Ilizarov S. Correction of tibial deformity with use of the Ilizarov-Taylor spatial frame. *J Bone Joint Surg Am.* 2006;88(suppl 4):156–174.
31. Rozbruch SR, Helfet DL, Blyakher A. Distraction of hypertrophic nonunion of tibia with deformity using Ilizarov/Taylor Spatial Frame: report of two cases. *Arch Orthop Trauma Surg.* 2002; 122:295–298.
32. Rozbruch SR, Herzenberg JE, Tetsworth K, Tuten HR, Paley D. Distraction osteogenesis for nonunion after high tibial osteotomy. *Clin Orthop Relat Res.* 2002;394:227–235.
33. Rozbruch SR, Kleinman D, Fragomen AT, Ilizarov S. Limb lengthening and then insertion of an intramedullary nail: a case-matched comparison. *Clin Orthop Relat Res*. 2008;466:2923–2932.
34. Rozbruch SR, Pugsley JS, Fragomen AT, Ilizarov S. Repair of tibial nonunions and bone defects with the Taylor Spatial Frame. *J Orthop Trauma.* 2008;22:88–95.
35. Ruta D, Garratt A, Abdalla M, Buckingham K, Russell I. The SF 36 health survey questionnaire: a valid measure of health status. *BMJ.* 1993;307:448–449.
36. Sabharwal S, Kumar A. Methods for assessing leg length discrepancy. *Clin Orthop Relat Res*. 2008;466:2910–2922.
37. Sen C, Kocaoglu M, Eralp L. The advantages of circular external fixation used in high tibial osteotomy (average 6 years follow-up). *Knee Surg Sports Traumatol Arthrosc*. 2003;11:139–144.
38. Seybold D, Gessmann J, Muhr G, Graf M. Deformity correction with the Taylor spatial frame after growth arrest of the distal radius: a technical note on 2 cases. *Acta Orthop*. 2008;79:571–575.
39. Sharma L, Song J, Felson DT, Cahue S, Shamiyeh E, Dunlop DD. The role of knee alignment in disease progression and functional decline in knee osteoarthritis. *JAMA.* 2001;286:188–195.
40. Siapkara A, Nordin L, Hill RA. Spatial frame correction of anterior growth arrest of the proximal tibia: report of three cases. *J Pediatr Orthop B.* 2008;17:61–64.
41. Sluga M, Pfeiffer M, Kotz R, Nehrer S. Lower limb deformities in children: two-stage correction using the Taylor spatial frame. *J Pediatr Orthop B*. 2003;12:123–128.
42. Sprenger TR, Doerzbacher JF. Tibial osteotomy for the treatment of varus gonarthrosis: survival and failure analysis to twenty-two years. *J Bone Joint Surg Am.* 2003;85:469–474.
43. Taylor JC. Taylor Spatial Frame. In: Rozbruch SR, Ilizarov S, eds. *Limb Lengthening and Reconstruction Surgery.* New York, NY: Informa; 2007:613–637.
44. Tellisi N, Fragomen AT, Ilizarov S, Rozbruch SR. Lengthening and reconstruction of congenital leg deficiencies for enhanced prosthetic wear. *Clin Orthop Relat Res.* 2008;466:495–499.
45. Tsaridis E, Sarikloglou S, Papasoulis E, Lykoudis S, Koutroumpas I, Avtzakis V. Correction of tibial deformity in Paget's disease using the Taylor spatial frame. *J Bone Joint Surg Br.* 2008;90:243–244.
46. Tsumaki N, Kakiuchi M, Sasaki J, Ochi T, Yoshikawa H. Low-intensity pulsed ultrasound accelerates maturation of callus in patients treated with opening-wedge high tibial osteotomy by hemicallotasis. *J Bone Joint Surg Am.* 2004;86:2399–2405.
47. Watanabe K, Tsuchiya H, Matsubara H, Kitano S, Tomita K. Revision high tibial osteotomy with the Taylor spatial frame for failed opening-wedge high tibial osteotomy. *J Orthop Sci*. 2008;13:145–149.
48. Weale AE, Lee AS, MacEachern AG. High tibial osteotomy using a dynamic axial external fixator. *Clin Orthop Relat Res.* 2001;382:154–167.
49. Whitehouse MR, Livingstone JA. Taylor Spatial Frame application with the aid of a fine wire half frame. *J Orthop Trauma*. 2008;22:276–281.