Pediatric and Adolescent Applications of the Taylor Spatial Frame

MICHAEL PALOSKI, DO, MBA; BENJAMIN C. TAYLOR, MD; CHRISTOPHER IOBST, MD; KEVIN J. PUGH, MD

As a result of reading this article, physicians should be able to:

1. Describe the basic fundamentals and parts of the Taylor Spatial Frame (TSF) and understand how they work together to produce the desired results.

2. Appreciate examples and outcomes of how the TSF can be applied to pediatric and adolescent patients to correct congenital and traumatic limb deformity and to acutely treat traumatic injuries.


4. Gain a foundation for the usefulness of the TSF in pediatric and adolescent patients to spark further study to expand on its use and indication.

ABSTRACT

Limb deformity can occur in the pediatric and adolescent populations from multiple etiologies: congenital, traumatic, posttraumatic sequelae, oncologic, and infection. Correcting these deformities is important for many reasons. Ilizarov popularized external fixation to accomplish this task. Taylor expanded on this by designing an external fixator in 1994 with 6 telescoping struts that can be sequentially manipulated to achieve multiaxial correction of deformity without the need for hinges or operative frame alterations. This frame can be used to correct deformities in children and has shown good anatomic correction with minimal morbidity. The nature of the CME article and determining if these objectives match your individual learning needs.

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of the construct and length of treatment affects psychosocial factors that the surgeon and family must be aware of prior to treatment. An understanding of applications of the Taylor Spatial Frame gives orthopedic surgeons an extra tool to correct simple and complex deformities in pediatric and adolescent patients.

The field of orthopedics was largely founded on the principles of deformity correction. Pediatric and adolescent patients present unique challenges to orthopedic surgeons given their propensity for growth, their bone morphology, and the location of the physis. Different methods of treatment for congenital, traumatic, posttraumatic, oncologic, and infection-related deformities have been proposed in the pediatric and adolescent populations. Each method has the goal of restoring anatomical alignment and, in turn, improving the patient’s quality of life. Stimulated by the work of the Russian orthopedist Gavriil Ilizarov, interest exists in external methods to perform gradual correction of long bone and joint deformities caused by various etiologies.1 The Taylor Spatial Frame (TSF) (Smith & Nephew, Memphis, Tennessee) was developed to enhance what many felt were treatment shortcomings with the Ilizarov frame, namely a steep learning curve and the difficulty of performing complex multi-axis corrections in a single step.

**TAYLOR SPATIAL FRAME**

The TSF (Figure 1) was developed in 1994 by Dr J. Charles Taylor and his brother, Harold Taylor, an engineer.2 The TSF consists of external metal rings connected to bone via half pins, wires, or both. The rings are then connected to each other by 6 individually numbered and color-coded telescoping struts in the manner of a Stewart platform (flight simulator). The 6 struts are arranged in a hexapod configuration and can be lengthened or shortened in unison to achieve the desired correction. With this design, each of the 6 axes of deformity can be addressed sequentially or simultaneously (Table 1). The struts are made in several overlapping sizes to accommodate different lengths necessary for treatment.

The TSF is integrated with online computer software (www.spatialframe.com). This software generates a schedule describing how to adjust each strut to achieve the desired correction. Information entered by the surgeon into the program allows the computer to visualize how the frame is attached to the patient and its relationship to the deformity using projective geometry. Projective geometry is the mathematical concept that makes it possible to define radiograph projections in mathematical terms.3 This concept was developed by Michel Chasles, who realized that the positioning of an object in 6 axes could be replicated by moving a nut along a threaded screw. The vector in which this deformity moves is termed the Chasles axis.3

Three basic methods are used to apply the TSF: chronic deformity, rings first, and total residual deformity.4 In the chronic deformity method, ring types, sizes, and locations are chosen preoperatively, and a construct is built to match the deformity. Treatment is then designed to bring the struts to neutral alignment (all struts are equal length) and the rings parallel to correct the deformity. In the rings first method, the rings are first applied perpendicular to each bone segment and then connected with the struts. Similar to the chronic deformity method, treatment is designed to bring the struts to neutral and the rings parallel. The third method, total residual deformity, is the most commonly used technique. With the total residual program, the software will provide a plan to straighten the deformity even if the rings are mounted in a nonorthogonal fashion, ie, it has the ability to correct a crooked bone even with a crooked frame. This is an extremely powerful aspect of the system because it lets the surgeon make unlimited adjustments to the deformity correction program at any point in time to obtain the desired correction.

Two concepts regarding the TSF need to be explained to understand the software. The first concept involves the identification of a reference fragment. Traditional orthopedic teaching is to analyze a deformity by describing the position of the distal fragment relative to the position of the proximal (reference) fragment. In the Spatial Frame software, the surgeon must determine which fragment will be the reference fragment. All deformity measurements are made based on the position of the corresponding fragment to this reference fragment. Either the proximal or distal fragment can be chosen as the reference fragment. By convention, the smaller of the 2 fragments is usually chosen as the reference fragment because the shorter distanc-

<table>
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<td>Coronal plane angulation (varus, valgus)</td>
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<td>Sagittal plane angulation (procurvatum, recurvatum)</td>
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<td>Axial rotation (internal rotation, external rotation)</td>
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**Figure 1:** Photograph of the Taylor Spatial Frame.
es create less potential for measurement error. To prevent errors, once a fragment is designated the reference fragment, it must remain the reference fragment throughout the correction process.

The second concept with the TSF is that of the origin and corresponding point. Once the reference fragment is determined, a point in space along that fragment (usually along the mechanical axis of the fragment) must be chosen. This point—the origin—is the point around which all future corrections will revolve. The origin is typically a convenient spot that is identifiable on both the anteroposterior and lateral radiographs, such as a bone spike in a fracture or the center of rotation angulation in a chronic deformity. The corresponding fragment will then have a second point—the corresponding point—which is a point in space used to coincide with the origin before the deformity occurred. The software will then devise a plan to move the corresponding point back to the origin, correcting the deformity.

After the rings are placed, the software requires 13 data points to compute the final alignment of the struts necessary to correct the deformity. These data points are divided into 3 categories: the deformation parameters, the frame parameters, and the mounting parameters. The 6 deformation parameters are determined from the preoperative biplanar radiographs and the clinical examination of the patient. They represent the 6 possible axes of deformity in the x, y, and z planes (coronal plane angulation, sagittal plane angulation, rotation, coronal plane translation, sagittal plane translation, and axial deformity). The rotational deformity must be assessed clinically by examining the patient’s limb alignment. However, the other 5 deformities are determined by analyzing the deformity on the orthogonal radiographs. These measurements of coronal angulation (varus/valgus), coronal (medial/lateral) translation, sagittal (apex anterior/posterior) angulation, sagittal (anterior/posterior) translation, and axial (short/long) deformity should be recognizable as the standard parameters examined in any deformity analysis.

After the 6 deformity parameters are entered, the next set of information the computer needs is the frame parameters. The frame parameters consist of 3 data points: the size of the proximal ring, the size of the distal ring, and the size of the struts used to connect the 2 rings. This information is easily obtained by recording the ring and strut sizes directly from the patient’s frame as it is assembled. If an open ring is used, such as a 2/3 ring, the software gives the surgeon an opportunity to describe where the open portion of the ring is located relative to the 6 struts.

The final 4 data points are the mounting parameters. This information allows the computer to understand where the ring on the reference fragment has been mounted relative to the origin. The center of the ring is identified in the coronal plane, and the distance from this point to the origin in the axial plane is measured and recorded. The second point needed is the amount of translation (medial or lateral) between the center of the ring and the origin in the coronal plane. The third point is the amount of translation (anterior or posterior) between the center of the ring and the origin in the sagittal plane. The final data point is the relative amount of rotation between the orientation of the limb and the orientation of the ring. In most cases involving the tibia, no rotation of the ring is needed. However, in the femur or the humerus, some rotation of the ring on the limb may be necessary to create a best fit for the patient. If this occurs, then the software needs to know the amount of rotation to correctly calculate the final strut settings.

Once these 13 data points are entered, the software can then begin to calculate how to correct the deformity. The final step is to determine the speed of the correction process. The surgeon has the ability to control the rate at which this correction occurs. In an acute fracture setting, surgeons may want the deformity to be corrected completely at once. In a chronic deformity correction, surgeons may choose to correct the deformity slowly over a period of days to weeks. Surgeons can enter the desired speed of correction (eg, 1 mm per day) and the software will produce a daily strut adjustment regimen that will achieve the complete correction at the desired speed. Surgeons also have the opportunity to identify a critical structure that should not be adjusted faster than the desired speed of correction. For example, a correction of a valgus deformity in the tibia has the potential to injure the peroneal nerve if done too quickly. Surgeons can input the estimated location of the peroneal nerve relative to the origin and then set a safe speed for the deformity correction relative to the movement of this critical structure. This structure, called the structure at risk, can be anything (eg, skin, nerve, vessel, or bone cortex) that the surgeon does not want to move too fast or too slow.

**BIOMECHANICS OF THE TAYLOR SPATIAL FRAME**

The TSF has been compared with the Ilizarov frame in terms of its biomechanical stability and in its accuracy of correction. Due to the octahedron design of the TSF, it has 1.1 times greater axial, 2 times greater bending, and 2.3 times greater torsional stiffness than the Ilizarov frame. The mechanical accuracy using manual adjustment of the struts for deformity correction has been measured to within 0.7° and 2 mm. A clinical study by Manner et al compared the accuracy of correction of the TSF with that of the Ilizarov frame. A total of 208 deformities in 155 patients over 20 years were reviewed; 129 cases were treated with the TSF and 79 cases were treated with the Ilizarov frame. All deformities, including congenital, acquired, and idiopathic, were considered. Overall, no residual deformity was present in 90.7% of the cases treated with the TSF compared with 55.7% of the cases treated with the Ilizarov frame. With increasing dimensions of deformity, the authors
found an increasing amount of residual deformity in both constructs, but the TSF showed superiority to the Ilizarov frame in achieving correction in all subgroups. For 2-dimensional corrections, the aim of treatment was achieved in 91.8% of TSF cases compared with 48.6% of Ilizarov cases (P < .05). For 3-dimensional corrections, the aim of treatment was achieved in 91.1% of TSF cases compared with 28.6% of Ilizarov cases (P < .05). For 4-dimensional corrections, the aim of treatment was achieved in 66.7% of TSF cases and was not achieved in any Ilizarov cases. However, significantly more cases of 3-dimensional (34.9% vs 17.7% [P < .05]) and 4-dimensional (7.0% vs 1.3% [P < .05]) deformity corrections were treated with the TSF than the Ilizarov frame.6

Pediatric Limb Deformity Correction

Ilizarov developed the important concepts of stable external fixation combined with minimal soft tissue disruption to obtain reliable healing of deformity corrections. Although good results have been achieved using the Ilizarov method, its largest criticisms are related to the steep learning curve of use and difficulty correcting multiaxial deformity with the frame.7 The TSF’s hexapod design and computer-aided strut adjustments make it easier to correct multiaxial deformity. Therefore, an increasing interest has been seen in using the TSF in pediatric limb deformity corrections. To date, the use of the TSF has been described in the literature for many usual and unusual conditions (Table 2).4,5,7,24 New applications of the TSF continue to be developed as experience with the device expands.

Blondel et al8 conducted a prospective study of 36 patients with a mean age of 11.1 years (range, 3 to 18 years) who required isolated limb lengthening of >4 cm, axial deformity correction, or both. Sixty-seven deformities were corrected with the TSF, including deformities of the femur, tibia, forearm, and ankle. Eighty-three percent of patients had no residual deformity at initial follow-up, and 91% of the patients eventually achieved correction objectives. The authors concluded that the TSF performed equally as well as the Ilizarov in limb lengthening while providing better rotational, translational, and residual deformity correction. The authors noted less pain in this study group by following the need for long-term analgesics and length of hospital stay. They postulated that this decrease in pain compared with other fixators may be due to the design of the construct evenly distributing stress among 6 struts instead of among 3 of 4 vertical stems, as in Ilizarov fixation.8

A study by Marangoz et al9 retrospectively reviewed 22 femurs in 20 patients (age range, 5.9 to 24.6 years) treated with a TSF for femoral deformity correction from multiple etiologies with a mean follow-up of 15.7 months (range, 4.5 to 35 months). Mean time in the frame was 6.2 months (range, 2.6 to 19 months). Mean limb lengthening was 4.9 cm at an average rate of 2.2 months/cm in 8 femurs. All but 1 patient was corrected to within 3° of normal with regard to femoral deformity. Valgus was corrected an average of 12.9°, varus was corrected 10.4°, and procurvatum was reduced an average of 23°.

Naqui et al7 reviewed their experiences with congenital and acquired deformity correction of 53 patients (mean age, 10.7 years) with 60 frames on 55 limbs. Their frame constructs included single and stacked TSF frames and combination TSF–Ilizarov foot frames. Mean follow-up was 22 months (range, 12 to 59 months). Seventeen limbs underwent residual correction for leg-length discrepancy >15 mm or angulation >5° using the same frame construct. Ultimately, 40 limbs had no final deformity, 12 limbs had residual deformity accepted by the patient and surgeon (leg-length discrepancy <15 mm or angulation <5°), and 3 limbs and 3 patients needed further treatment. Of the 3 patients who needed further treatment, 1 had deformity recurrence of fibular hemimelia, 1 had aborted treatment of pseudarthrosis of the tibia before regenerate formed, and 1 developed deformity due to a pseudoaneurysm at the regenerate site of a tibial pseudarthrosis thought to have occurred from pin site insertion near the long saphenous vein.7

A smaller study reported 5 patients with a mean age of 11 years (range, 6 to
16 years) treated for congenital and acquired deformities of the lower extremity (4 femurs and 1 tibia) with the TSF. All patients in this series had undergone prior operations or lengthening on the affected extremity. The authors achieved mean lengthening of 5.9 cm (range, 1.7 to 7.2 cm), mean sagittal angulation correction of 10.6° (range, 0° to 19°), and mean lateral translation of 12.6 mm (range, 0 to 33 mm).

Eidelman et al reviewed their experience with the TSF in treating patients with Blount’s disease using the TSF. Nineteen patients treated with TSFs with Ilizarov-type struts gained a mean length of 4.21 cm, with a lengthening index of 1.33 months/cm. The lengthening index for the TSF in this study is comparable with that of other studies. The author postulated that this increase in lengthening time is caused by the more complex, gradual correction in multiple planes in the TSF compared with the axial-only correction of the Ilizarov-type struts. For purely axial lengthening, the Ilizarov construct may have a shorter time to lengthening. However, most deformities involve >1 plane, and the ease of use and ability to correct multiple axes at once with the TSF may decrease overall length of time in the fixator.

**Blount’s Disease**

Blount’s disease is a condition of unknown etiology that causes multiplanar deformity of the tibia, including proximal tibia vara, proximal tibia procurvatum, and internal tibial torsion. Given the multiplanar deformity and limb-length inequality created by the disorder, the TSF is potentially an ideal treatment method for Blount’s disease. A representative case is shown in Figure 2. Fibular osteotomy may be performed concurrently with the proximal tibia osteotomy to aid with correction, but a recent study has shown that fibular osteotomy may not be necessary.

Feldman et al reported their experience treating patients with Blount’s disease using the TSF. Nineteen patients (22 tibias) with a mean age of 9.9 years (range, 3 to 16 years) and Langenskiold stages II-V were treated gradually with a TSF for a mean of 14.6 weeks (range, 9 to 24 weeks). Twenty-one tibias were corrected to within 3° of normal in both the sagittal and coronal planes. Internal tibial torsion decreased from a mean of 17.5° (range, 10° to 30°) to a mean of 0°, mechanical axis deviation decreased from a mean of 53.9 mm (range, 31 to 120 mm) to a mean of 1.4 mm (range, 0 to 4 mm), and mean varus decreased from a mean of 16.5° (range, 8° to 50°) to a mean of 0° (range, −2° to 2°). They attribute their excellent results to the gradual correction affording the ability to make subtle changes effortlessly using residual correction without returning to the operating room.

Bar-on et al reported 4 patients with a mean age of 8.1 years (range, 6.9 to 9.1 years) who were treated for severe, early-onset Blount’s disease (Langenskiold stages V and VI), with elevation of the medial tibial plateau, lateral hemiepiphysiodesis, and proximal tibial metaphyseal osteotomy and gradual correction with a TSF. Mechanical axis was corrected to 0° in 3 patients and 6° in the other patient. Tibial torsion was corrected to 0° in 3 patients and 15° of external rotation the other patient. Lastly, preplanned overlengthening of 1 to 4 cm was achieved in all patients. Two patients had a recurrence of 7° of varus that stabilized after 1 year. The authors attributed the recurrence to either an incomplete lateral epiphysiodesis or to mild distal femoral varus. Eidelman et al’s experience treating 4 patients with adolescent Blount’s disease (mean age at surgery, 14.5 years) with the TSF was also positive. They achieved restoration of the mechanical axis to within normal parameters in all 4 patients.

The question as to whether acute or gradual correction in Blount’s disease is more effective was investigated using the TSF. Feldman et al evaluated acute vs gradual correction in 32 patients and found statistically greater angular and translational correction with the gradual
Foot and Ankle

The TSF can be used to treat complex foot and ankle deformities in children and adolescents. Foot and ankle treatments for idiopathic clubfoot, teratologic clubfoot, metatarsal shortening, tibial shortening, arthrogryposis, rigid equinovarus secondary to spina bifida, hindfoot deformity, and ankle deformity have been reported. Eidelman and Katzman reported 13 patients (14 frames) with a mean age of 8 years (range, 3.5 to 14 years) at the time of surgery who had complex foot deformities that were treated with the TSF. Eleven of the patients had correction of their deformities, but almost all had some type of complication. The most common complication encountered was metatarsalangeal joint dislocation, prompting the authors to routinely pin all toes with Kirschner wires and attach them to the frame during treatment. Another case series by Eidelman and Katzman reported their experience in treating rigid clubfoot and congenital vertical talus with the TSF in 7 patients (age range, 4 to 16 years) with arthrogryposis. They used the frame with osteotomies or for soft tissue distraction, and the most common complication was pin-site infection, occurring in >50% of the patients.

A more recent article by Hassan and Letts reviewed their experience with congenital foot deformity correction with the TSF in patients aged between 6 and 14 years. Most patients had untreated congenital talipes equinovarus treated with soft tissue releases and midfoot osteotomies prior to frame application. All patients in the study achieved plantigrade placement of their feet. Superficial pin tract infection was the most common problem encountered. The authors support this method of treatment for rigid congenital foot deformities because it allows gradual correction to protect soft tissue and structures at risk, it allows full weight bearing in the frame to desensitize the feet to the new anatomic position, and it allows for unrestricted examination of the circulation and neurological function of the foot during treatment.

TRAUMA
Acute Trauma

Given the appropriate indications and applications, the TSF is an excellent treatment option for acute and delayed pediatric trauma. Several articles in the literature demonstrate successful management of pediatric trauma with the TSF. Al-Sayyad used the TSF to treat 10 high-energy, unstable tibial fractures in 9 patients (mean age, 12 years 3 months), and retrospectively reviewed the outcomes (mean follow-up, 3.1 years). The TSF was constructed, intraoperative radiographs were taken, and the Total Residual program was immediately used to determine strut length for anatomic reduction. These values were dialed into the struts, and the patient was awakened from anesthesia. The fractures healed over a mean of 18 weeks (range, 12 to 29 weeks), and the patients remained in the frame for a mean of 19 weeks (range, 12 to 33 weeks). All fractures united without loss of reduction, remanipulation, or malunion, and all patients were doing well and involved in sports at last follow-up. No patient sustained a refracture.

Blondel et al treated 11 patients (mean age, 12 years) with tibial fractures with the TSF. Three had loss of reduction in a cast, 3 had open fractures, 4 had associated fractures and closed head injury, and 1 had compartment syndrome. The frame was applied using traction as the only reduction maneuver, and radiographs were taken later on postoperative day 1 to determine a turning schedule. Radiographically, 9 patients achieved reduction without residual deformation, I had a flexion deformity of 8°, and 1 had overgrowth of 7 mm. The authors placed 5 patients in Sarmiento braces after frame removal to limit the risk of refracture, but they did not
define their criteria as to which patients would receive the brace.18

Eidelman and Katzman19 reported their experiences in treating 13 patients (mean age, 11.1 years) with 13 complex tibial fractures, 9 open fractures, and 4 closed fractures. In this series, all patients were treated with another fixation method (monolateral external fixator, cast, or Ilizarov frame) prior to the TSF. Mean time to TSF application was 31.8 days (range, 3 to 165 days). Acute correction was not performed in any case, but the turning schedule began on postoperative day 1. Twelve patients healed in normal anatomical alignment and 1 developed proximal tibial valgus 1 year after frame removal that was treated with medial hemiepiphysiodesis. The authors stressed gradual correction (1 mm/day) to prevent neurovascular compromise, unnecessary pain, and soft tissue injury in patients who present when fracture reduction is delayed.19

### Posttraumatic Correction

Figure 3 demonstrates how the TSF can be used to correct posttraumatic deformities. In this case, the patient suffered a physeal fracture of his proximal tibia when he was 13 years old. He developed a complex deformity consisting of shortening, external rotation, negative tibial slope, and valgus with mechanical axis deviation. All of these deformities were addressed and corrected simultaneously with a single application of the TSF.

The TSF can be used for correction of posttraumatic deformities in the subacute or delayed setting. Eidelman et al20 treated 18 patients (mean age, 13.1 years) with various posttraumatic deformities with a TSF. These deformities included malunions and growth arrests (primarily of the tibia), 3 distal femoral deformities, and 1 distal radial physeal-related deformity. Osteotomies were performed, and the frame was removed after a mean of 12.3 weeks (range, 8 to 24 weeks). Follow-up was a minimum of 2 years after frame removal. In all patients, the mechanical axis was restored, length equalization was achieved, all patients were pain free, and all patients had regained preoperative range of motion.

Ganger et al21 retrospectively reported their experience in treating 22 patients with 25 posttraumatic lower-limb deformities with the TSF. They analyzed the accuracy of correction, complication rate, clinical outcome, and duration of treatment. Although mean age at time of injury was 14.3 years (range, 2 to 46 years), mean age at time of correction was 22.7 years (range, 12 to 48 years). Mean follow-up was 21.1 months (range, 12 to 43 months). At final follow-up, all sagittal and axial deformities were corrected, and 2 cases showed a residual mechanical axis deviation. One patient sustained a refracture of the distal femur with trauma 8 months after removal of the frame. One patient sustained late bowing of the proximal tibia after noncompliance with weight bearing. The authors support the use of the TSF for correction of posttraumatic deformity because of the good radiographic results and minimal morbidity associated with the TSF.21

A case report by Siapkara et al22 described their experiences treating deformity due to anterior growth arrest of the proximal tibia after trauma in 3 patients. They were able to achieve correction of hyperextension and restoration of anatomical posterior proximal tibial angle (posterior tibial slope) in all 3 patients in a mean of 34.7 days (range, 32 to 37 days), with a mean total time in the frame of 18.3 weeks (range, 16 to 20 weeks).

Although the vast majority of posttraumatic corrections reported involve lower-extremity deformities, the TSF has also been applied to posttraumatic deformity of the upper extremity.20,23 Seybold et al23 treated 2 boys with a posttraumatic pseudo-Madelung deformity after an epiphyseal fracture of the distal radius. With the TSF, the surgeons were able to gradually achieve multplanar correction of the distal radius, reduction of the distal radioulnar joint as confirmed by computed tomography, and restoration of pronation and supination to anatomical in a mean of 27 days (range, 23 to 31 days) of distraction and a mean time in the frame of 31 days (range, 79 to 92 days). Preoperative pronation and supination of patient 1 was 40° and 30°.

### Table 4

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<thead>
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<th>Pin Grade</th>
<th>Appearance</th>
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<tr>
<td>1</td>
<td>Pain or erythema, no drainage</td>
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<tr>
<td>2</td>
<td>Pain, erythema, and serous drainage</td>
</tr>
<tr>
<td>3</td>
<td>Pain, erythema, and purulent drainage</td>
</tr>
<tr>
<td>4</td>
<td>Pain, erythema, and purulent drainage with radiographic osteolysis</td>
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<tr>
<td>5</td>
<td>Ring sequestrum or osteomyelitis</td>
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### Table 3

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<td>Joint stiffness4,9,20</td>
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</tr>
<tr>
<td>Breakage of wires4,7</td>
</tr>
<tr>
<td>Pseudoaneurysm7</td>
</tr>
<tr>
<td>Artery injury11</td>
</tr>
<tr>
<td>Nerve palsy5,13</td>
</tr>
</tbody>
</table>

Although the vast majority of posttraumatic corrections reported involve lower-extremity deformities, the TSF has also been applied to posttraumatic deformity of the upper extremity.20,23 Seybold et al23 treated 2 boys with a posttraumatic pseudo-Madelung deformity after an epiphyseal fracture of the distal radius. With the TSF, the surgeons were able to gradually achieve multplanar correction of the distal radius, reduction of the distal radioulnar joint as confirmed by computed tomography, and restoration of pronation and supination to anatomical in a mean of 27 days (range, 23 to 31 days) of distraction and a mean time in the frame of 31 days (range, 79 to 92 days). Preoperative pronation and supination of patient 1 was 40° and 30°.
and of patient 2 was 30° and 20°, respectively; postoperative pronation and supination were 80° and 90° for patient 1 and 90° and 70° for patient 2, respectively.23

**Complications**

The most common complication in the studies reviewed was superficial pin-site infection (Table 5).3 Gordon et al20 developed a pin-tract infection grading system (Table 4). Grade 0 is defined as a clean pin; grade 1 is pain, erythema, or tenderness around the pin site; grade 2 has the characteristics of grade 1 infections but with serous drainage; grade 3 also has the characteristics of grade 1 infections but with purulent drainage; grade 4 is similar to grade 3 but shows radiographic osteolytic changes to the pin sites; and grade 5 has an associated ring sequestrum or osteomyelitis. Most pin-site infections reviewed for this article resolved with oral antibiotics.7,18,20,25,26 Few reports exist on the superficial infection progressing to a deep infection12 or osteomyelitis.

Another complication specific to this type of treatment is fracture of the regenerated bone. One study recommended dynamizing the frame prior to frame removal.5 In another study, the authors placed their patients in Sarmiento braces after frame removal to protect the regenerated bone. One study recommended dynamizing the frame prior to frame removal.5

Therefore, it is beneficial to protect the bone after frame removal to prevent injury to the newly formed bone. Delayed union12,20 and nonunion7 can occur with frame treatment; however, malunion should theoretically be avoidable with the TSF.

Given the gradual correction and need for solidification of the regenerated bone, many patients must wear the TSF for months. This invariably leads to joint stiffness, even if the frame does not span the joint involved.27 This is likely due to the decreased use of the affected extremity given the size, weight, and psychosocial factors imparted to the patient from the frame. Joint stiffness usually resolves after frame removal; however, physical therapy21,22 is sometimes necessary. Joint subluxation15 may sometimes occur if a joint is spanned and lengthening occurs.5

Beginning early physical therapy9,24 or

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**Table 5**

<table>
<thead>
<tr>
<th>Complication</th>
<th>Optimal Outcome</th>
<th>Obstacle(s)</th>
<th>Minor Complication</th>
<th>Major Complication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle contracture</td>
<td>Contracture resolves nonoperatively</td>
<td>Contracture treated successfully operatively before the end of treatment</td>
<td>Contracture remains at end of treatment, but then resolves nonoperatively</td>
<td>Contracture requires tendon and capsule releases after treatment ended</td>
</tr>
<tr>
<td>Joint luxation</td>
<td>Subluxation treated nonoperatively</td>
<td>Joint subluxation that requires operative treatment but resolves before the end of treatment</td>
<td>Subluxation left after removal of the device that is able to be treated nonoperatively</td>
<td>Subluxation left after removal of the fixator that must be treated operatively</td>
</tr>
<tr>
<td>Axial deviation</td>
<td>Axial deviation treated nonoperatively</td>
<td>Axial deviation treated operatively during course of fixator</td>
<td>Axial deviation heals in position less than 5°</td>
<td>Axial deviation heals in position greater than 5°</td>
</tr>
<tr>
<td>Neurologic injury</td>
<td>Distraction-related nerve dysfunction that recovers during treatment</td>
<td>Neurologic injury requiring prophylactic decompression</td>
<td>Residual neurologic dysfuntion at the end of treatment</td>
<td>Residual neurologic dysfunction at the end of treatment</td>
</tr>
<tr>
<td>Vascular injury</td>
<td>N/A</td>
<td>N/A</td>
<td>Residual neurologic dysfuntion at the end of treatment</td>
<td>Residual neurologic dysfunction at the end of treatment</td>
</tr>
<tr>
<td>Premature consolidation</td>
<td>Premature consolidation treated nonoperatively</td>
<td>Premature consolidation treated operatively</td>
<td>Surgeon discontinues lengthening due to premature consolidation</td>
<td>Surgeon discontinues lengthening due to premature consolidation</td>
</tr>
<tr>
<td>Delayed consolidation</td>
<td>Delayed consolidation treated nonoperatively</td>
<td>Delayed consolidation treated by addition of more pins</td>
<td>Delayed consolidation treated by bone grafting</td>
<td>Delayed consolidation treated by bone grafting</td>
</tr>
<tr>
<td>Pin-site problems</td>
<td>Pin-tract infections treated by local debridement, antibiotics, or pin removal</td>
<td>Addition of a new pin is required</td>
<td>Any true bone infection</td>
<td>Any true bone infection</td>
</tr>
<tr>
<td>Refracture</td>
<td>N/A</td>
<td>N/A</td>
<td>Buckle fracture; loss of &lt;1 cm of length; &lt;5° of angulation</td>
<td>Loss of &gt;1 cm of length; &gt;5° of angulation</td>
</tr>
<tr>
<td>Joint stiffness</td>
<td>N/A</td>
<td>N/A</td>
<td>Any joint stiffness</td>
<td></td>
</tr>
</tbody>
</table>

*References 4, 5, 7-9, 11, 12, 16, 18-21, 24, 25.*
stabilizing the joints during treatment\textsuperscript{15} may alleviate this problem.

One case of a pseudoaneurysm was reported in a patient due to a transfixion wire injuring the posterior tibial artery. The artery was embolized, the pin was repositioned, and the situation was ameliorated. Wire breakage,\textsuperscript{4,7} continued pain,\textsuperscript{8} and compartment syndrome\textsuperscript{8,18} have also been reported.

Paley\textsuperscript{28} developed a classification system of complications related to limb lengthening that can also be applied to other uses of the TSF, such as deformity or traumatic correction. He divides the situations into problems, obstacles, or complications. Problems are known, possible difficulties that occur either during or after fixation and resolve completely with nonoperative means. Obstacles are known, possible difficulties that occur during or after fixation and resolve completely with operative intervention. Complications are any local or systemic perioperative problems that remain unresolved after treatment is completed; complications can then be further classified as major or minor. Major complications are subclassified as those that interfere with the goals of original treatment and those that do not and require additional surgery after treatment. Minor complications resolve with nonoperative means (Table 5).

**Disadvantages**

The TSF has several disadvantages. First is the cost of the frame itself,\textsuperscript{5,19} Cost of the physical frame construct (rings, struts, and pins/wires) can range anywhere from $6000 to $12,000. Second, the smallest ring size is 105 mm and the largest ring size is 305 mm. In the pediatric and adolescent populations, smaller ring sizes than those available may be necessary to accommodate the smaller circumference of the extremities. A rare problem may occur in obese patients, such as those who may present with adolescent Blount’s disease, whom even the largest rings may not fit appropriately.

Another disadvantage may be the learning curve of the TSF. Although it is considered much easier to use and modify than the Ilizarov frame, some physicians still do not use the product because of its complexity. Those physicians may equate the complexity of the construct with the complexity of use. A learning curve exists not just for application of the TSF, but also for the indications of the frame and which patients and family would be able to psychologically handle the frame.

Another disadvantage of the TSF is the necessity for strict patient compliance. Although noncompliance is not exclusive to this type of treatment, patient compliance with the turning schedule is paramount to properly obtaining the appropriate correction. Gradual correction involves turning the struts at a rate of approximately 1 mm/day, either all at once or in divided turns. Patients and their families who either do not comply or are not willing to comply should not be selected as candidates for treatment with the TSF. Also, proper patient compliance with pin-site care is important to minimize and prevent infection. Noncompliance with pin-site care can result in superficial pin-site infections and, although the rates are low, this may lead to deep infection or osteomyelitis, which may have been prevented with proper care.

**Conclusion**

The TSF is a unique external orthopedic device that allows for acute and gradual deformity correction in multiple axes. The hexapod configuration of its struts allows simultaneous correction of multiaxial deformity, including limb lengthening. Pediatric and adolescent patients with congenital, traumatic, oncologic, or infectious-related deformities may benefit from this device. Many times, deformities are multiaxial and involve complex adjustments to achieve correction. Using computer assistance, the TSF allows the surgeon to correct the deformity and modify the correction with minimal effort.

When used in acute trauma, the TSF can easily hold anatomic alignment of the fracture fragments. The frame’s construct provides such stability that it allows for early weight bearing and range of motion, which assists fracture healing in trauma and regenerate formation in deformity correction and lengthenings.\textsuperscript{5,19} However, delayed union, malunion, and nonunion are still possibilities, even with early modifications of the frame.

The benefits of the TSF come with a price. Complications are associated with external fixation and dynamic frame treatment. Most of the studies reviewed reported pin-site infections, but almost all were corrected with oral or intravenous antibiotics. Fracture and deformity of the regenerate are also possible. Surgeons must use care in determining when to remove the frame and must reiterate to patients and families the importance of limb protection after frame removal. Psychosocial issues are also involved in treating pediatric and adolescent patients with an external fixator, and this must be realized and addressed preoperatively to obtain the best postoperative results. The literature supports that most psychosocial issues resolve after frame removal.\textsuperscript{29,34} Most of the studies reviewed were retrospective reviews, case reports, or case series with small numbers. It would not be difficult to create a prospective, randomized study comparing the TSF with other forms of treatment; however, given the cost of TSF treatment and importance of proper patient and family screening, these types of high-level studies may not be feasible. To date, no studies directly compare the TSF with other monolateral multiaxial fixator systems, such as the Multi-Axial Correction (Biomet, Parsippany, New Jersey). Future studies comparing time to deformity correction, time in the fixator, and final outcomes between these 2 constructs may be warranted.

The studies reviewed were thorough in reporting radiographic outcomes and, in a majority of cases, radiographic correction.
was achieved comparable with accepted anatomic norms or to the contralateral extremity. However, none of the studies reviewed used validated instruments, such as the SF-36, to assess subjective interpretation of treatment with the TSF. Although many patients had good radiographic outcomes, more studies focusing on specifics of functionality after treatment are warranted. Granted, this may be difficult with pediatric patients, but adolescent patients should be able to accurately rate their outcomes.

REFERENCES