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Submuscular Bridge Plating for Complex Pediatric Femur Fractures Is Reliable

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Abstract

Background Complex, high-energy pediatric femur diaphyseal fractures cannot be treated reliably by conventional methods: casting is not suitable for polytrauma and large children, external fixation is associated with a high rate of malalignment and refractures, elastic nails are unsuitable for unstable fractures and metaphyseal areas, and lateral trochanteric entry rigid nails cannot address proximal and distal fragments and need relatively large medullary canals. A few centers have reported that submuscular bridge plating (SBP) is associated with minimal complications, but these findings require confirmation.

Questions/purposes We asked whether SBP (1) reproducibly leads to union in unstable fractures with a low complication rate, (2) leads to reasonable alignment and leg length equality (3), is unaffected by age, weight, or location of fracture, and (4) is associated with no or minimal refracture after hardware removal.

Methods We retrospectively reviewed 60 fractures in 58 patients with pediatric diaphyseal femoral fractures treated with SBP from 1999 to 2011. The average age was 9 years. Forty (67%) of the fractures were unstable. Minimum followup was 2.4 months (average, 15.5 months; range, 2.4–50.6 months).

Results All fractures healed well and all patients returned to full activity. Two of the 58 patients (3%) had major complications leading to unplanned surgeries: one implant failure and one deep infection in an old open fracture. None of the patients developed clinically important malalignment or leg length discrepancy. Implant removal was performed in 49 patients without complications.

Conclusions SBP provided reliable fixation and healing for complex pediatric femur fractures and can have a broader application in the orthopaedic community. SBP is our preferred method for unstable fractures or fractures of the proximal and distal shaft.

Level of Evidence Level IV, therapeutic study. See the Instructions for Authors for a complete description of levels of evidence.

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Each author certifies that the institutions in which the study was performed (University Medical Center of El Paso and Texas Tech University Health Sciences Center) approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.
This work was performed at University Medical Center of El Paso (El Paso, TX, USA) and Texas Tech University Health Sciences Center (El Paso, TX, USA).

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Introduction

Femoral shaft fractures are among the most common musculoskeletal injuries in children requiring inpatient hospital admissions [10]. While spica casting is still a common treatment option for patients younger than 5 years with an isolated injury and minimal shortening (< 2 cm) [25], there is an emerging trend toward surgical treatment in older children [16, 30]. Elastic nails are usually used for stable fracture patterns of the middiaphysis in children weighing less than 45 kg (100 pounds) [7, 8, 15]. Unstable middiaphyseal fractures in heavier children and fractures located in the proximal or distal 1/3 of the diaphysis are more difficult to treat reliably with elastic nails [6–8, 15, 35, 38].

According to the current American Academy of Orthopaedic Surgeons (AAOS) Clinical Practice Guidelines concerning pediatric diaphyseal femur fractures [23], there is poor-quality evidence in support of any specific surgical treatment modality. Casting for high-energy injuries in children younger than 10 years needed repeated additional procedures in about ½ of the cases [32]. External fixation can be complicated by refracture, malunion, delayed union, pin tract infections, and unsightly scars [1, 28, 33, 37]. External fixation has been associated with a refracture rate of 22%, malalignment rate of 20%, and pin tract infection rate of 70% [28]. Rigid intramedullary devices are used routinely in adults, but in children there is a serious risk of damaging the vascular supply to the femoral head, resulting in avascular necrosis of the femoral head when using piriformis fossa or even greater trochanter entry points [2, 17, 18, 26]. Rigid nailing needs to be performed with an entrance point lateral to the tip of the trochanteric physis to avoid injury to proximal femur blood vessels and only in older patients who have a medullary canal large enough for nail passage. Very proximal and distal fractures are still difficult to treat with rigid nails [12, 18, 20, 26]. There is a risk for growth arrest of the greater trochanter apophysis resulting in coxa valga and heterotopic bone formation when violating the trochanteric physis [18]. Classical compression plating, with a long incision and more soft tissue damage, has a higher risk of infection and delayed healing, with a reported reoperation rate of 10% [3]. Submuscular bridge plating (SBP) for diaphyseal femur fractures was first reported for adult patients in the late 1990s [4, 39]. The procedure began to gain acceptance among orthopaedic surgeons and has started to be used in the pediatric population. It is part of the treatment algorithm recently published in the AAOS Clinical Practice Guidelines [23]. The advantages include a minimally invasive soft-tissue-preserving approach and relative stability that allows for early ROM (no casting or bracing is required) and reliable healing. In the AAOS guidelines, SBP is an option for treatment of children aged 11 years to skeletal maturity [23]. For patients younger than 11 years, the guidelines suggest the flexible nail as the main treatment. This works for stable fractures; however, proximal and distal fractures, spiral and complex fractures, and fractures in heavy children (> 40–45 kg) have higher complication rates (7% with prominent irritating nail, 10% with malalignment of 5°–10°, 70% needing additional immobilization) when treated by flexible nails [6, 7, 15].

Several authors have reported the use of SBP in series ranging from 27 to 51 patients [13, 21, 36]. These reports suggest fractures heal well with near-anatomic leg alignment and/or rotation and minimal leg length discrepancy (LLD). Further, the reoperation rate (for causes other than recommended plate removal) is low, ranging from 0% to 2%. However, these reports require confirmation of reproducibility.

We asked whether SBP (1) reproducibly leads to union in unstable fractures with a low complication rate, (2) achieves near anatomic alignment and leg length equality (3), is unaffected by age, weight, or location of fracture, and (4) is associated with no or minimal refracture after hardware removal.

Patients and Methods

We retrospectively reviewed prospectively collected data on 69 pediatric patients with diaphyseal femoral shaft fractures (72 fractures) treated with SBP from 1999 to 2011. Our main indications for SBP were displaced pediatric femur diaphyseal fractures that were (1) length unstable (with multiple fragments or spiral) and/or (2) with a short proximal or distal main fragment. The contraindications were active infection of the surgical site or severe contamination in cases of open fractures. Twelve fractures in 11 patients were excluded due to inadequate followup, leaving 60 fractures in 58 patients for inclusion. Twenty-three of these 58 patients were previously reported [21]. Of the 58 patients, there were 43 (74%) boys and 15 (26%) girls, with an average age of 9 years (range, 3.6–15.7 years) (Table 1). The average patient weight was 35.2 kg (range, 12.7–71.5 kg). The average time from injury to surgery was 1.9 days (range, 0–20 days) (Table 2). Minimum followup was 2.4 months (average, 15.5 months; range, 2.4–50.6 months). No patients were recalled specifically for this study and all data were obtained from medical records. High-energy trauma accounted for 39 injuries (65%), and 23 patients (38%) had multiple associated injuries. Automobile versus pedestrian mechanism was the most common cause (15 fractures, 26%), while falls and motor vehicle collisions accounted for 13 (22%) and nine (16%) fractures, respectively. One patient had osteogenesis imperfecta, and two patients sustained pathologic fractures through benign osseous lesions. Thirty-one of the 58 patients (52%) sustained either proximal or distal fractures.

Table 1. Patient demographic and fracture data

Variable	Value
Patient age (years)*	9.1 (3.6–15.7)
Weight (kg) *	35.2 (12.7–71.5)
Sex (male:female) (number of patients)	43:15 (74%:26%)
Laterality (right:left) (number of fractures)	35:25 (59%:41%)
Open fractures (number of fractures)	4 (7%)
High-energy injury (number of fractures)	39 (65%)
Multiple trauma (number of fractures)	23 (38%)
Mechanism (number of fractures)	
Auto vs pedestrian	15 (26%)
Motor vehicle crash	9 (16%)
Fall < 1.5 m (5 feet)	10 (17%)
Other	7 (12%)
All-terrain vehicle crash	6 (10%)
Injured from falling object	4 (7%)
Football	4 (7%)
Fall > 1.5 m (5 feet)	3 (5%)
Fracture type (number of fractures)	
A1	12 (20%)
A2	9 (15%)
A3	16 (27%)
B1	6 (10%)
B2	10 (17%)
B3	2 (3%)
C1	2 (3%)
C2	2 (3%)
C3	1 (2%)
Fracture level (number of fractures)	
Proximal 1/3	19 (32%)
Middle 1/3	29 (48%)
Distal 1/3	12 (20%)
Length unstable (number of fractures)	40 (67%)

* Values are expressed as mean, with range in parentheses.

Fracture type was classified according to the OTA/AO classification [27] as follows: A (simple, transverse or short oblique), B (wedge-shaped middle fragment), or C (complex, with multiple fragments). There were 37 (62%) Type A fractures, 18 (30%) Type B, and 5 (8%) Type C. Fracture instability was defined as length unstable if it was complex or spiral (the length of the fracture was twice as long as the diameter of the femur at the level of the fracture) [11, 40]. Forty (67%) were length-unstable fractures. Fracture level was separated into the proximal, middle, and distal 1/3 of the diaphysis. Proximal 1/3 diaphyseal fractures occurred in 19 (32%) patients, middle 1/3 fractures in 29 (48%), and distal 1/3 fractures in 12 (20%).

The fractures were treated by one of 10 surgeons. The details of the technique were originally published by Kanlic et al. [21] in 2004. A brief description of the technique is given here. The patient was intubated, fully relaxed (for easier reduction), and positioned on the flat, radiolucent table. If there was substantial comminution, both lower extremities were prepared and draped, allowing for intraoperative comparisons between the two extremities for rotation and length. A small bump was put beneath the hip on the affected side, and the thigh was positioned on folded sheets or on a radiolucent triangle (easier manual traction and lateral c-arm view). A 4.5-mm stainless steel straight plate or with built-in anterior curvature was selected (occasionally, 3.5-mm plate was used for small patients). The plate length spanned the femur from the greater trochanter to the distal femur and was chosen intraoperatively using fluoroscopy. Plate ends were slightly bent to better fit the metaphyseal flares, staying away from the vulnerable physis. The proximal incision (a few centimeters long) started at the level of the vastus ridge on the greater trochanter. The fascia lata was opened and a periosteal elevator was used to elevate the vastus lateralis muscle from the bone without damaging the periosteum. The plate was introduced submuscularly and epiperiosteally by gently advancing it toward the opposite end, and alignment was maintained by manual traction. Use of a

Table 2. Operative data

Variable	Value
Days from injury to surgery*	1.9 (0–20)
Operative time (minutes)*	89 (44–160)
Fluoroscopic time (seconds)*	56 (15–214)
Estimated blood loss (mL)*	121 (20–500)
Plate length (number of holes)*	13 (5–22)
Number of screws proximal*	3 (2–5)
Number of screws distal*	3.1 (2–5)
Number of holes centrally left unfilled*	4.7 (1–15)
Surgeon (number of fractures)	
Surgeon 1	42
Surgeons 2–10	18
Plate (number of fractures)	13
4.5-mm LC-DCP broad	23
4.5-mm LCP broad	18
3.5-mm LC-DCP	6
4.5-mm narrow LCP	3
4.5-mm LC-DCP narrow	2
4.5-mm LCP distal femoral plate	2
3.5-mm LCP	3
3.5-mm proximal femur DHS	1
4.5-mm proximal femur LCP	1
LCP distal femoral condylar plate	1

* Values are expressed as mean, with range in parentheses; LC-DCP = limited contact dynamic compression plate; LCP = locking compression plate; DHS = dynamic hip screw.

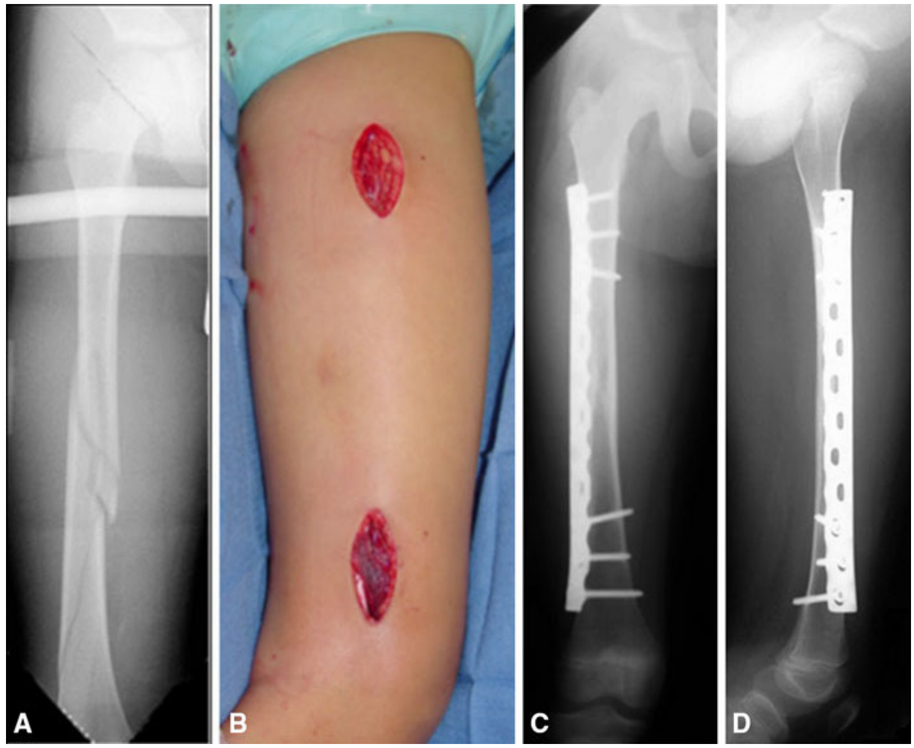

Fig. 1A–D (**A**) A radiograph shows a midshaft femur wedge fracture with fracture line extension in the distal main fragment. The patient was 8.2 years old who sustained the injury after a fall while skateboarding. (**B**) An intraoperative photograph shows the incisions used to fix the fracture. (**C**) AP and (**D**) lateral radiographs show the healed fracture fixed using a 4.5-mm broad stainless steel plate after 16 months, just before plate removal.

femoral distractor or performing the surgery on a fracture table could replace manual traction if the surgeon did not have enough assistance or excessive, resistant shortening was present due to delay in treatment. A K-wire was placed through the plate hole at one end, paying attention to keep the plate centered on the bone on the lateral view. The position of the opposite end of the plate was determined with intraoperative fluoroscopy and another incision was made at that level. For distal fractures, it was easier to introduce the plate via the distal (metaphyseal area) incision first. Indirect reduction was obtained by traction, adjustment of the bump or triangle position, or pushing with a hammer or reduction (F-shaped) tool. After acceptable reduction and plate position were achieved, a second K-wire was introduced through a hole at the other end of the plate for temporary fixation. After additional evaluation and necessary adjustments were made, classical (nonlocking) screws were placed at each of the plate ends (three at each side, using a clustered screw pattern, Fig. 1). If indirect reduction could not be obtained because of soft tissue interposition or substantially displaced multiple fragments, an incision at the fracture level was made and reduction was achieved by finger manipulation or with a bone hook. To preserve reduction, temporary K-wires were deployed on both sides of the fracture ends through the same middle incision in the plate holes, and K-wires were then replaced by screws that improved reduction pulling the fragment toward the plate, achieving the so-called dispersed or near-near, far-far construct (Fig. 2). An example of SBP in a proximal femur fracture is shown (Fig. 3).

Recorded operative time was on average 89 minutes (range, 44–160 minutes), and fluoroscopy time was on average 56 seconds (range, 15–214 seconds). The average plate length was 13 holes, with an average of three screws per main fragment. The estimated blood loss was on average 121 mL (range, 20–500 mL).

No postoperative immobilization was needed; patients were mobilized within 24 hours using a walker and with the recommendation to be toe touch weightbearing for 6 weeks. Protected weightbearing was hard to achieve in this pediatric population: most children did not follow our recommendation and were fully weightbearing at their followup visits.

Followup visits at clinic were scheduled around 2 weeks postoperatively for wound check (no radiographs taken), 6 weeks for assessment of bony healing, 3 months for assessment of gait, strength, and possible return to sport activity, and 8 to 12 months for discussion about implant removal. Use of a walker was discontinued if the patient was able to bear weight without pain and radiographs showed progression of healing with bridging of three cortices on orthogonal views by callus. We recommended avoiding competitive sports for 3 to 6 months (depending on the size and quality of callus). We advised implant removal approximately 1 year after injury and explained the risks were minimal if the child was healthy. Patients were counseled that the incision would be slightly longer

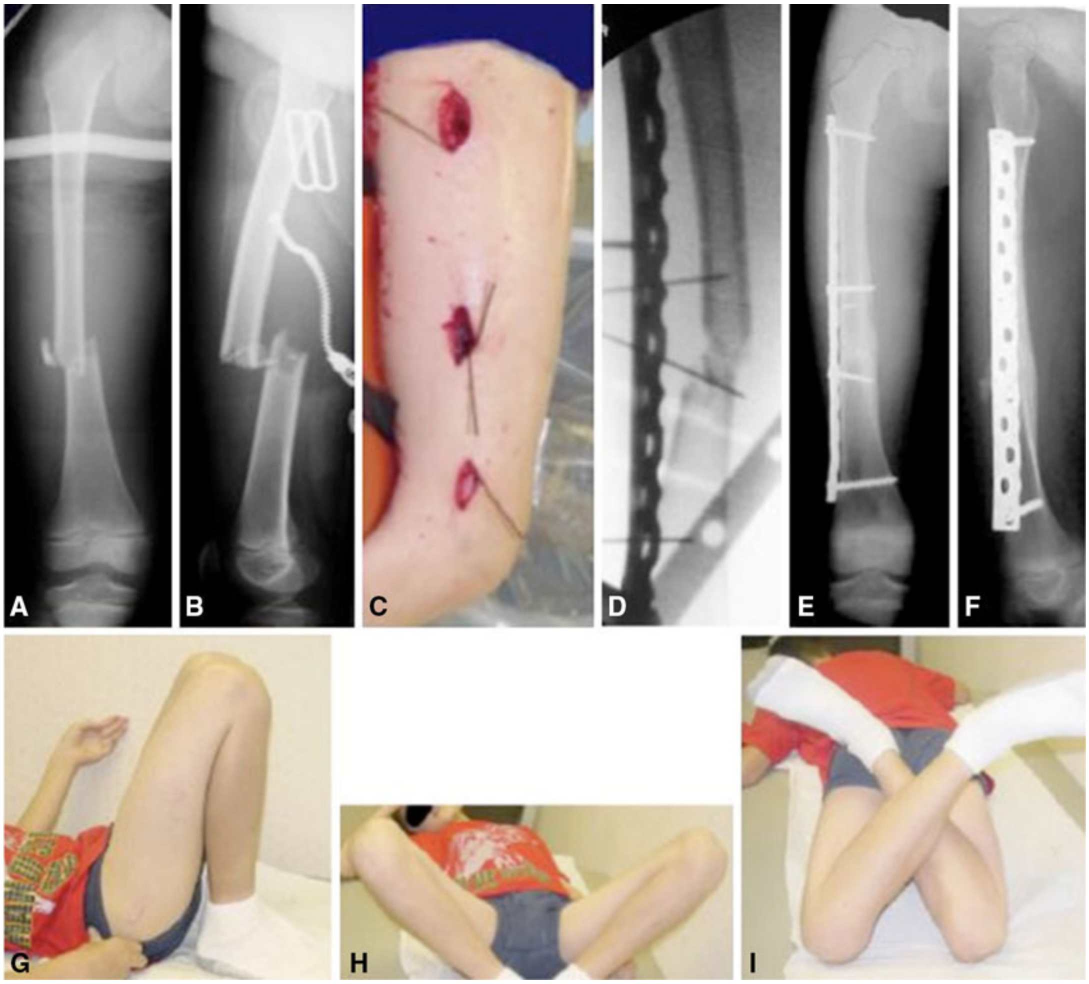

Fig. 2A–I (**A**) AP and (**B**) lateral views show a completely displaced midshaft femur fracture with separated wedge fragment. (**C**) An intraoperative photograph shows the incisions, middle one needed for direct reduction and (**D**) an intraoperative image shows temporary fixation with K-wires. (**E**) AP and (**F**) lateral views show the completely healed fracture fixed with screws in dispersed mode after 4.5 months. (**G**, **H**, **I**) Clinical photographs show ROM just before hardware removal 13 months after the injury.

than the original one. Also, by having the plate removed, they would avoid possible future complications, such as stress shielding, periprosthetic fractures, valgus deformity, and change of the implant position due to continued growth of the bone. Delay in hardware removal is associated with bone overgrowth over the plate, making the surgery more difficult. There is also a concern for hardware being in the way of future joint arthroplasties. After plate removal, we recommended at least 6 weeks of decreased activity (no contact sports).

Complications were classified as major when unplanned surgical intervention was needed or substantial functional problems developed, eg, deep infection, persistent nerve damage, substantial rotational or angular malalignment (varus-valgus $> 15°$ in children younger than 5 years, $> 10°$ in children from 6–10 years old, and $> 5°$ in children older than 10 years/procurvatum-recurvatum deformity $> 20°$ in children younger than 5 years, $> 15°$ in children from 6–10 years old, and $> 10°$ in children older than 10 years [9]), persistent limp, persistent hip or knee stiffness, LLD, malunion, and nonunion. Minor complications did not require surgical intervention and did not result in substantial functional problems, eg, implant irritation, superficial wound infection, and transient nerve palsy. A scanogram was performed on 23 patients approximately 1 year after the index procedure; in the remaining 35 patients, we determined leg length by clinical examination (flexion of the both hips and knees and assessment of the femur length at the level of the patella).

Results

SBP in treatment of complex pediatric femur fractures is reproducible (10 surgeons) and reliable (minimal rate of complications). All fractures healed. The average time for

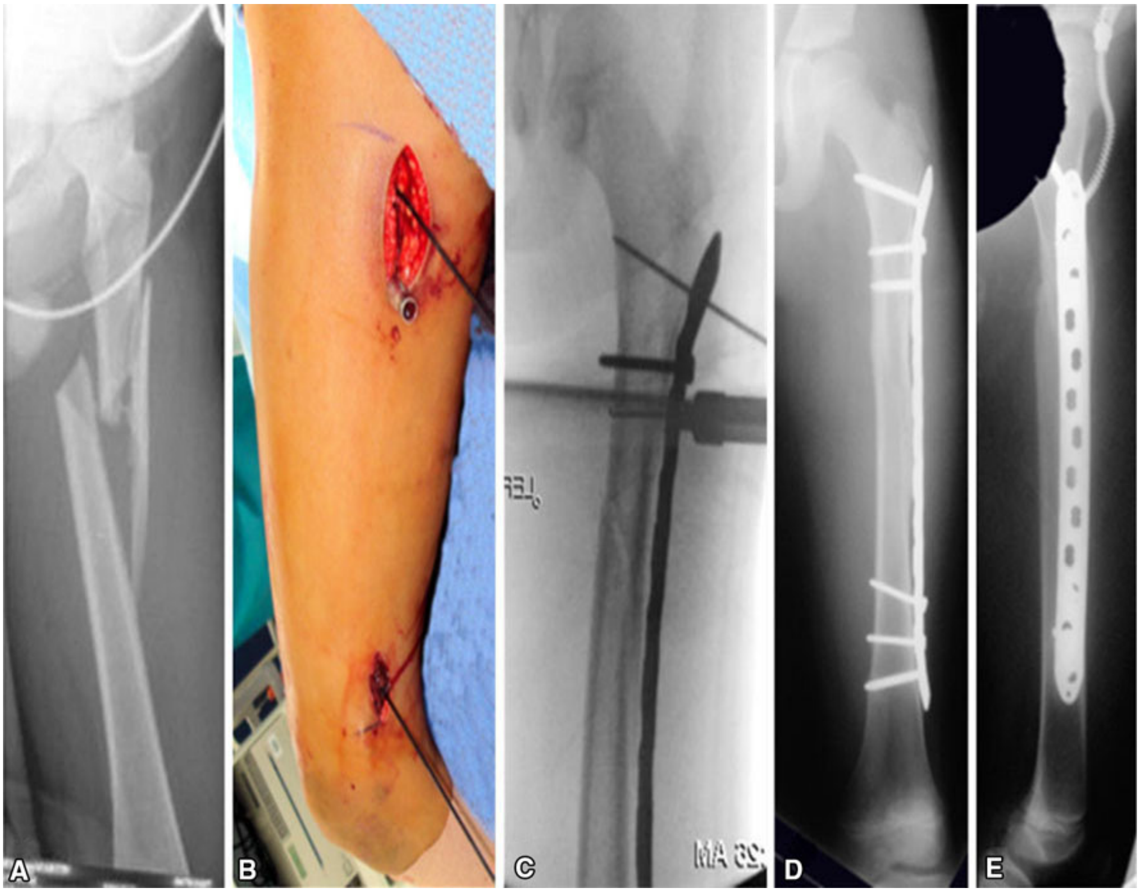

Fig. 3A–E (**A**) A radiograph shows the left femur with a complex proximal ⅓ femur fracture after a high-energy injury in 7.4-year-old boy. (**B**) An intraoperative photograph shows the incisions and the locking sleeve in the proximal wound used for easier plate control. (**C**) An intraoperative radiograph shows the reduced fracture and fixation in progress. (**D** and **E**) AP view presenting two locking screws in shorter, proximal fragment for better fixation and lateral radiograph show the healed femur 1 year after injury.

20 patients to bridge two cortices was 6.7 weeks, the average time for 30 patients to bridge three cortices was 9.3 weeks, and the average time for 38 patients to bridge four cortices was 13.3 weeks.

Two major complications (unplanned surgeries) occurred (3%). The first was a polytraumatized patient transferred to us 1 day after injury with fractures of the pelvis, bilateral femurs (one open), humerus, and tibia (open). The open femur side was treated by irrigation and débridement, removal of loose bone pieces, and external fixation for 2 weeks followed by conversion to SBP. The patient developed a postoperative hematoma and deep infection, which responded well to serial débridements, antibiotic bead placement, and eventual hardware removal. The other patient was an 8-year-old patient with substantial shortening of an oblique fracture in which a dispersed pattern of screws was used with a 16-hole 3.5-mm titanium plate. He walked on it soon after discharge and returned for followup after 6 weeks with a bent plate that eventually broke after an additional 4 weeks. The plate was replaced with a stronger, 4.5-mm stainless steel plate through the slightly enlarged previous incision sites. The fracture healed uneventfully thereafter. We subsequently changed our practice to use the 4.5-mm stainless steel plates for all fractures except in very small femurs (Fig. 4). We no longer use titanium plates.

Minor complications included symptomatic hardware in three patients that all resolved after hardware removal (Table 3), superficial wound infection in two patients that responded to oral antibiotic therapy, and one temporary peroneal nerve palsy that resolved spontaneously after 3 months. One patient with a distal displaced fracture and severe head injury was not able to comply with partial weightbearing and had a slight loss of fixation (antecurvatum and valgus deformity) after 2 weeks. A long leg cast was applied for 5 additional weeks, which allowed satisfactory healing and full function (Fig. 5).

None of our patients had clinically important malrotation or shortening noticed by parents or treating surgeons. Thirteen of the 23 patients with a scanograms showed no

Fig. 4A–F (**A**) An AP view shows a short oblique shortened fracture in a 9-year-old boy hurt as a passenger on a motorcycle. (**B**) AP and (**D**) lateral views show the 16-hole 3.5-mm titanium plate that bent after 5 weeks. (**D**) An AP view shows the broken plate 10 weeks after surgery. (**E**) AP and (**F**) lateral views 14 months after injury show the 4.5-mm stainless steel plate used to replace the broken plate through slightly enlarged original incisions with uneventful healing and full recovery.

Table 3. Complications

Complication	Number
Malalignment/malrotation	0
Symptomatic hardware	3
Superficial wound infection	2
Hardware failure	
Requiring casting	1
Requiring surgery	1
Temporary peroneal nerve palsy	1
Functional deficit	0
Leg length discrepancy (average, 9.9 mm)	10

evidence of LLD while 10 had an average LLD of 9.9 mm (range, 10 mm short to 20 mm long). None of the patients with an LLD required a shoe lift or had any functional deficit at latest followup.

There was no difference between children weighing more than 45 kg and those weighing less than 45 kg in regard to complications (major and minor), alignment, rotation, or healing time. The only two failures of fixation that we had were in children weighing around 20 kg, and none of the patients who weighed more than 45 kg had failure of fixation. Also, there were no differences in the above parameters among different fracture locations (proximal/middle/distal), and no major complications occurred in proximal or distal fractures.

Forty-eight of 58 patients (83%, 49 femurs) had their implant(s) removed at an average of 13.5 months (range, 4.6–28.4 months) with no complications.

Discussion

Pediatric femoral shaft fracture is a common injury. Casting, external fixation, flexible nails, compression plating, and SBP have all been used as a treatment option. The current AAOS Clinical Practice Guidelines [23] suggest there is poor-quality evidence in support of any specific surgical treatment modality for diaphyseal femur fractures in children. For patient younger than 11 years, the guideline has the flexible nail as the main treatment. While these appear appropriate for stable fractures, proximal and distal fractures, spiral and complex fractures, and fractures in heavy children (> 40–45 kg) have higher complication rates when treated by flexible nails [6, 7, 15]. Very proximal and distal fractures are still difficult to treat with rigid nails, which also require relatively large medulla to accommodate the nails [12, 18, 20, 26]. Classical compression plating requires a long incision and is associated with more soft tissue damage, a higher risk of infection, a higher rate of delayed healing [3]. According to the AAOS guidelines, SBP is an option for treatment of children aged 11 years to skeletal maturity [23]. While a number of studies [13, 14, 21, 36] report SBPs are associated with

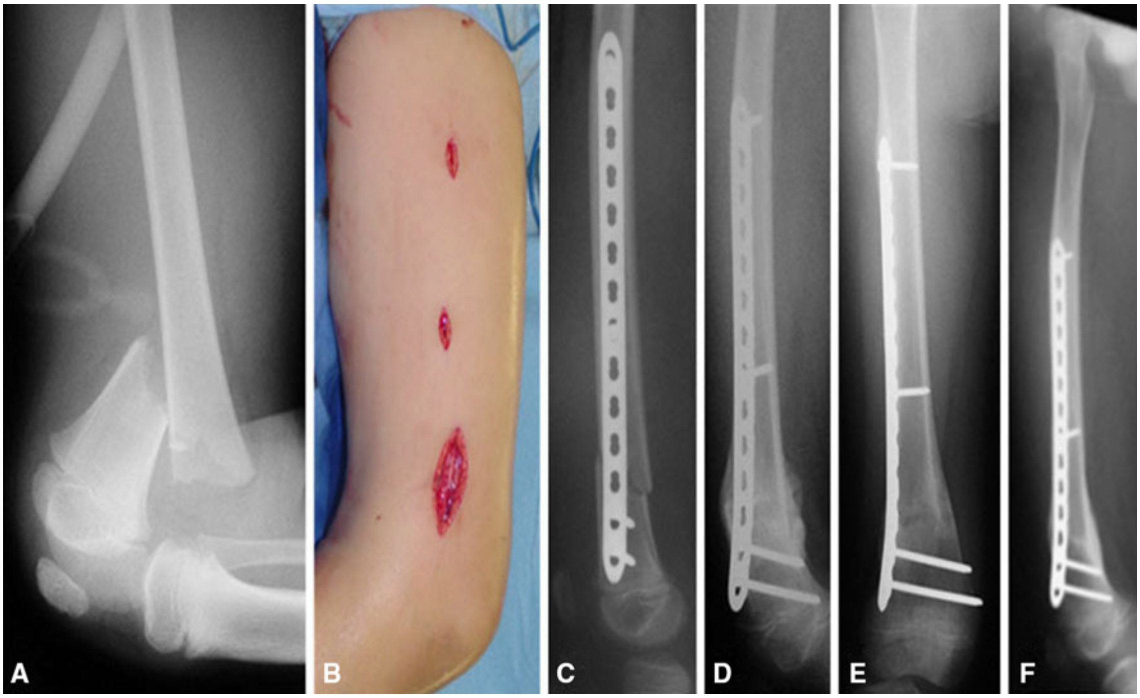

Fig. 5A–F (**A**) A lateral view shows the distal femur with a displaced fracture after high-energy injury in 7.11-year-old boy who also had a severe brain injury. (**B**) A photograph shows the incisions used for fracture fixation. (**C**) A postoperative lateral view shows near-anatomic reduction. (**D**) A lateral view taken after 7 weeks shows the patient lost some reduction walking on it after 2 weeks and had to be casted for 5 weeks. (**E**) AP and (**F**) lateral views show the fracture healed in good position after 4.5 months.

high rates of healing, reasonable alignment, and low reoperations rates, their findings require confirmation and proof of reproducibility. We therefore asked whether SBP (1) reproducibly leads to union in unstable fractures with a low complication rate, (2) leads to reasonable alignment and leg length equality (3), is unaffected by age, weight, or location of fracture, and (4) is associated with no or minimal refracture after hardware removal.

Readers should be aware of the limitations of the study. First, we lacked a direct comparison group. However, we had a relatively large number of pediatric patients with SBP (the largest review to date) and prospectively collected data: the primary group had 72 fractures with adequate followup data for 60. Second, 11 patients (19%) were excluded due to inadequate followup. We do not believe these exclusions would influence the key findings. Third, the first 40% of patients had routine scanograms for evaluation of possible LLDs; the rest of them were evaluated by clinical examination only (which we found sufficient).

Our observations and those of others suggest SBP can be used to treat pediatric femur fractures with minimal complications and reoperation rate, especially for length-unstable fractures and patients with high-energy fractures. Most of our fractures (67%) were length-unstable fractures. All fractures healed and patients returned to full activity. Our complication rate was minimal. Similar results were found in other studies that addressed submuscular plating in regard to the effectiveness of the procedure to treat femur fracture, healing, and complications (Table 4) [13, 14, 21, 36].

SBP for complex fractures reliably provides better alignment and leg length than other forms of treatment (casting, external fixation, or flexible nailing). None of our patients had clinically important malrotation or shortening or required a shoe lift. The relative stability achieved by biologic bridge plating fixation has been adequate, consistent, and reliable in our report and others [13, 14, 21, 24, 34, 36]. Multiple studies have shown, for comminuted and length unstable fractures, flexible nails are associated with a high rate of malunion [1, 5–8, 11, 15, 19, 35, 38]. Sink et al. [35] reported eight of their 39 patients (21%) required unplanned surgeries and found 10 of the 15 patients (66%) in the unstable fracture group had either fracture shortening or angulation.

The results with SBP were not affected by patient age, weight, or fracture location. There is no weight restriction for this technique. Moroz et al. [29] noted a poor outcome was observed in heavier patients treated with flexible nails and concluded patients weighing more than 49 kg were five times more likely to have a poor outcome. SBP is not affected by the size of the medullary canal, and thus there is no age restriction (we had patients as young as 4 years). In our patient population, there were 4- and 5-year-old

Table 4. Comparison of our study with those in the literature reporting results of treatment for pediatric femoral fractures

Study	Number of patients	Treatment method	Followup (months)	Results
Kanlic et al. [21]	51 (including the first 23 in our current study)	Submuscular plating	14.2	Excellent results with no significant malrotation or angulation; 8% of patients developed leg length discrepancy of 5–23 mm; average time to bridging of 3 and 4 cortices of 9 and 14 weeks, respectively; hardware removed in 36 of 51 patients; refracture occurred in one patient (70-kg individual) with an originally unrecognized pathologic fracture through a nonossifying fibroma when hardware was prematurely removed at 6 months
Sink et al. [36]	27	Submuscular plating	11	No patient had coronal plane angulation > 10° or shortening > 5 mm; one patient had sagittal plane malalignment > 10°; average time to bridging of 3 to 4 cortices of 11.7 weeks; hardware electively removed in 18 patients 6 to 8 months postoperatively with no complications
Hedequist et al. [13]	32	Locked plating	Until definitive radiographic union	All fractures went on to union with one case of valgus malalignment > 10°; no other complication; 7 patients underwent hardware removal at an average of 11 months from the index procedure with no noted complications
Pate et al. [31]	22	Submuscular plating (removal at an average of 9 months)	Not mentioned	No fractures seen after hardware removal; 7 patients required a more extensive procedure to remove the plate than was required during the initial procedure, due to leading edge overgrowth predicted by radiographs during the healing process and not related to the timing of plate removal
Sink et al. [35]	39	Titanium elastic nails	11	8 patients (21%) required unplanned surgeries; 10 of the 15 (66%) patients in the unstable fracture group had either fracture shortening or angulation
Moroz et al. [29]	234 fractures	Flexible nails	14.2	Poor outcome observed in heavier patients; patients with weight > 49 kg were 5 times more likely to have poor outcomes
Keeler et al. [22]	78 (80 fractures)	Rigid intramedullary lateral entry nails	25	No malunion, delayed union, osteonecrosis of the femoral head, or increase neck shaft angles; mean age of 12.9 years; 88% of the fractures in midshaft
Current study	58 (60 fractures)	Submuscular bridge plating	15.5	All fractures healed with no clinically significant malrotation or malalignment and minimal leg length discrepancy; all patients returned to full functional activity; no difference in results between different fractures locations or in children weighing > 45 kg; two fixation failures and two unplanned surgeries; implant removed in 49 femurs with no complications

patients with very narrow medullary canals not able to accommodate rigid nails. For rigid nailing, the size of the medullary canal should be big enough to accommodate the nail. In a study by Keeler et al. [22], the mean patient age was 12.9 years, compared to an average age of 9.1 years in our study. Another major advantage of SBP is that it can be used for very proximal and distal fractures. More than ½ of the fractures (52%) in our study were either proximal or distal compared to 12% in the study of Keeler et al. [22].

We believe there is benefit for a healthy patient with a well-healed fracture to remove hardware approximately 1 year after fixation. Forty-eight of our patients (83%) had hardware removal at an average of 13.5 months after the original procedure. We found the procedure is benign, even if light bone overgrowth over the plate is present [31].

This study confirms earlier studies reporting SBP using a soft-tissue-sparing [13, 21, 31, 36], biologic approach and relative stability fixation provides reliable fracture healing with a minimal rate of complications. SBP is our preferred method for treatment of high-energy, complex pediatric femoral shaft fractures with length-unstable fracture patterns (multiple fragments, spiral) and fractures involving metaphyseal areas (with short proximal or distal main fragments). We believe this procedure can play an important role in the treatment of pediatric femur fractures.

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