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# Rigid intramedullary nail fixation of traumatic femoral fractures in the skeletally immature

Christopher Del Balso, MBBS, MSc, FRCSC, Debra Bartley, MD, FRCSC, Megan Cashin, MD, FRCSC, Timothy Carey, MD, FRCSC, Abdel Rahman Lawendy, MD, PhD, FRCSC

**Abstract**

**Objective:** To determine the rate of femoral head osteonecrosis, and other complications following rigid intramedullary (IM) nail fixation of traumatic diaphyseal femur fractures through the greater trochanter in the skeletally immature.

**Design:** Retrospective review, case series.

**Setting:** Level I academic trauma center.

**Patients/Participants:** One hundred forty-eight traumatic pediatric diaphyseal femur fractures in 145 patients treated with rigid IM nail fixation from November 1, 2004 to December 31, 2018.

**Intervention:** Rigid intramedullary nail fixation of traumatic diaphyseal femur fractures through a trochanteric start point in the skeletally immature.

**Main outcome measurement:** Rate of osteonecrosis of the femoral head.

**Results:** Sixty-five fractures in 64 skeletally immature patients met inclusion criteria. Motor vehicle collisions were implicated in 32 fractures. Of the 65 fractures, 5 were open. All rigid IM nails were anterograde with a trochanteric start point. Mean radiographic follow-up was 27.4 ± 8.1 months. Twenty-two patients experienced postoperative pain and/or hardware irritation, with 24 patients (36.9%) undergoing reoperation for hardware removal. No occurrences of infection, malunion, nonunion, refracture, venous thromboembolism, fat embolism, significant leg length discrepancy, or femoral head osteonecrosis were documented. Two cases of heterotopic ossification were observed, 1 requiring surgical excision, yielding a complication rate of 3.1%.

**Conclusions:** No cases of femoral head osteonecrosis were observed following treatment of 65 traumatic diaphyseal femur fractures with rigid IM nailing through the greater trochanter with a mean radiographic follow-up of 27 months. Rigid IM nail fixation with a trochanteric start point is both safe and efficacious for management of diaphyseal femur fractures in the skeletally immature.

**Keywords:** complications, femur, intramedullary nail, osteonecrosis, pediatrics, skeletally immature

## 1. Introduction

Traumatic diaphyseal femur fractures are a significant cause of morbidity in the pediatric population with a prevalence of 1.4% to 1.7% of all pediatric fractures,[1,2] and an annual incidence of 20 fractures per 100,000 children.[3] Numerous treatment options exist including traction, hip spica cast immobilization, external fixation, submuscular plate fixation, flexible IM nailing, and rigid IM nailing. Appropriate fracture management is dependent on factors such as patient age, weight, skeletal maturity, fracture pattern and location, mechanism of injury, and the presence of concomitant injuries. Rigid IM nail fixation has been the standard of care in diaphyseal femoral fractures in adults for in excess of 30 years.[4,5] Recognized advantages over other treatment methods include shorter length of hospital stay, early mobilization and weight-bearing, diminished muscle atrophy, early knee motion, minimal risk of malunion or secondary fractures, and early return to work or school. In the skeletally immature, these very same benefits are observed. However, the potential risk of femoral head osteonecrosis has called into question the safety of rigid IM nailing. In 2009, the American Academy of Orthopaedic Surgeons (AAOS) released a clinical practice guideline on the management of pediatric diaphyseal femoral fractures stating that rigid IM nailing, flexible IM nailing, and submuscular plating may all be treatment options in patients older than 11 years.[6] Osteonecrosis of the femoral head,

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*Division of Orthopaedic Surgery, Schulich School of Medicine and Dentistry, Western University, London Health Sciences Centre, Victoria Hospital, London, Ontario, Canada*

*[*] Corresponding author. Address: Division of Orthopaedic Surgery, Schulich School of Medicine and Dentistry, Western University, London Health Sciences Centre, Victoria Hospital, 800 Commissioners Road East, London, Ontario, Canada N6A 5W9. Tel: +1 519-667-6815, fax: +1 519-667-6816. E-mail address: christopher.delbalso@lhsc.on.ca (C. Del Balso).*



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although rare, can be a devastating complication of rigid IM nailing. The blood supply to the femoral head is delivered by the deep branch of the medial femoral circumflex artery and has been described extensively.[7,8] Damage to any of the branches of the medial femoral circumflex artery in the proximity of the piriformis fossa may cause femoral head osteonecrosis and subsequent collapse. Not surprisingly then, the entry site of the rigid IM nail for fixation of diaphyseal femur fractures has been speculated to have an effect on rates of femoral head osteonecrosis and has been the subject of systematic review.[9] The piriformis fossa (PF), tip of the greater trochanter (TGT), and the lateral greater trochanter (LGT) have been used as starting points in an attempt to avoid the blood supply to the femoral head. Osteonecrosis rates of 2% for the PF, and 1.4% for the TGT have been reported.[9]

For greater than a decade, our center has utilized rigid IM nail fixation through the greater trochanter (GT) for pediatric femoral fractures with successful clinical outcomes. The purpose of the present investigation was to determine the incidence of femoral head osteonecrosis, and other complications associated with rigid IM nailing of traumatic diaphyseal femur fractures through the GT in the skeletally immature by reviewing cases at a single trauma centre.

## 2. Methods

A retrospective chart and radiographic review of all traumatic pediatric diaphyseal femur fractures treated with rigid IM nail fixation at London Health Sciences Centre, Victoria Hospital from November 1, 2004 to December 31, 2018 was performed. One hundred forty-eight fractures in 144 pediatric patients were identified. Patients with pathological fractures, inadequate follow-up (<12 months), or who were skeletally mature at the time of fracture fixation were excluded from the study (Fig. 1). Skeletal maturity was determined by closure of the distal femoral epiphyseal plate. Sixty-five fractures in 64 skeletally immature patients were included in the analysis. Mean patient age was 13.4 ± 1.4 years (SD). Three patients were under 11 years of age, 17 were under 13, and 49 of 64 patients were under 15 years of age. Mean patient weight was 59.1 ± 14.2 kg (SD).

All rigid IM nails were anterograde with a GT start point. Fifty-five fractures in 54 patients were treated with the Smith and Nephew (Memphis, Tennessee) Trigen Adolescent Trochanteric Antegrade Nail (TAN). This nail allows for a lateral trochanteric entry via 12 degrees of lateral offset. The nail has specifications of left and right, with an 8.5 mm diameter in lengths from 26 cm to 40 cm. A single 130-degree proximal locking screw may be placed in an anterograde or retrograde fashion. Two distal locking screws may be placed with a static configuration or a single locking screw may be placed in the dynamic configuration. Implanted Adolescent TANs ranged from 8.5 mm × 28 cm to 8.5 mm × 40 cm. Ten fractures were treated with the Smith and Nephew (Memphis, Tennessee) Trigen Trochanteric Antegrade Nail (TAN) with a 10 mm diameter. This nail is used in the adult population and differs primarily with respect to its proximal locking configuration, which allows for femoral or recon locking modes. The Trigen TAN has 5 rather than 12 degrees of lateral offset requiring a TGT start point. Implanted TANs ranged from 10 mm × 36 cm to 10 mm × 42 cm.

Patient electronic and paper charts were reviewed for demographic information, fracture mechanism, concomitant injuries, surgical and perioperative details and complications. Preoperative patient radiographs were evaluated for the purpose of fracture characterization. The magnitude of comminution was graded by the percentage of diaphyseal width that was fragmented, adapted from the Winquist classification.[10] Grade 0 depicts no fragmentation at the fracture site, grade I fragmentation involves less than 25% of the diaphyseal width, grade II (25% to <50%), grade III (50% to <75%), and grade IV (75%–100% or segmental). Postoperative radiographs were evaluated for union, malunion, nonunion, refracture, or heterotopic ossification. Union was defined as the presence of bridging callus on 3 of 4 cortices on orthogonal views. Malunion was defined as femoral shortening equal to or greater than 2 cm, mal-rotation of more than 10 degrees, or angulation in any

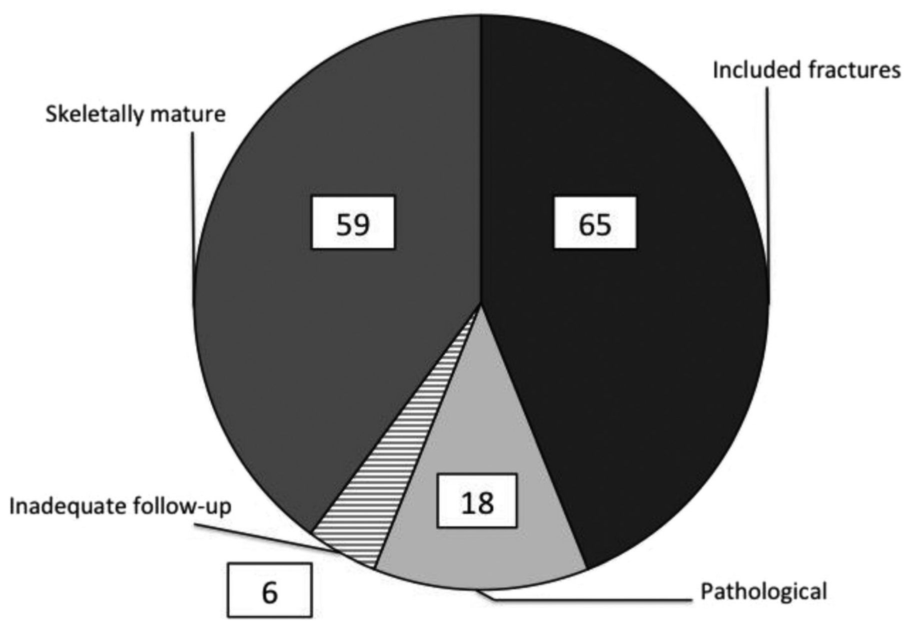


**Figure 1.** Summary of traumatic diaphyseal femur fractures treated with IM nail fixation through the TGT (n = 148). Patients with pathological fractures (n = 18), inadequate follow-up (<12 months) (n = 6) and those who were skeletally mature at the time of fracture fixation (n = 59) were excluded from the study.

plane greater than 10 degrees. Nonunion was defined as failure to show any progressive change in the radiographic appearance for at least 12 weeks after the period of time during which normal fracture union would be thought to have occurred. At each follow-up appointment, patients were evaluated clinically for the presence of ongoing pain, limp, and/or leg length discrepancy. Leg length discrepancy was considered significant if equal to or greater than 2 cm. Final radiographs were reviewed for evidence of osteonecrosis.

### 2.1. Operative Technique

Fifty-one of 65 fractures were placed in skin traction prior to operative fixation. Two fractures were placed in skeletal traction. Mean time from initial presentation to operative fixation was 12.2 ± 6.8 hours (SD). Mean operative time was 78.8 ± 28.0 minutes (SD). Of 19 poly-traumatized patients, 10 underwent operative management of concomitant injuries at the same time as rigid nail implantation. In 5 cases, a nonorthopaedic surgical specialty was involved. These patients were removed from the analysis of operative time. One patient underwent bilateral rigid IM nail fixation for bilateral, closed femoral fractures.

Patients were positioned supine on a fracture table with the foot of the operative leg in a padded boot. The contralateral leg was flexed at the hip and knee, abducted at the hip, and placed in a padded leg holder or "scissored" to allow ample room for fluoroscopy. Traction was applied to achieve a provisional reduction and restore length. The fractured extremity was prepared and draped using split sheets to allow access to the hip and thigh. A longitudinal incision was made proximal to the greater trochanter. The incision was made through to the fascia to allow palpation of the tip of the greater trochanter. The optimal entry point for the Adolescent TAN is located lateral to the tip of the greater trochanter, approximately 12 degrees from the anatomical axis in the AP plane and in-line with the intramedullary canal in the lateral plane. A 3.2 mm tip threaded guide pin was inserted into the trochanteric region and position was checked in AP and lateral planes with image intensification. The femoral canal was then opened using either a 12.5 mm or 14 mm entry reamer dependent on the nail utilized (Adolescent TAN vs TAN). The threaded guide pin was then removed and a 3.0 mm ball-tipped guide wire was advanced distally through a reducer. The reducer was then removed and the position of the guide pin was confirmed in the AP and lateral planes to ensure the distal extent of the nail was left 1 to 3 cm proximal to the distal femoral physis. A ruler was utilized to measure implant length. A flexible reamer under power was used progressing to 10 mm to ensure passage of the 8.5 mm Adolescent TAN (11.5 mm for the 10 mm TAN). Once the nail was passed, length and alignment were verified, and proximal interlocking was carried out using the nail insertion jig. Distal interlocking was carried out using a freehand technique after carefully confirming appropriate rotation. No cast immobilization was required, and patients were instructed to weight-bear as tolerated with crutches.

This study was approved by the University of Western Ontario Research Ethics Board (London, ON, Canada). Data analysis was performed using IBM SPSS for Mac OS X, Version 21 (Chicago, Illinois). Data are presented as mean ± SD.

## 3. Results

Sixty-four patients with 65 traumatic diaphyseal femoral fractures met inclusion criteria for our retrospective review. Fifty fractures occurred in male patients while 15 fractures occurred in females. Forty-two fractures of the right femur were documented compared with 23 fractures of left femur. Forty-six of 65 fractures were isolated fractures. Nineteen patients were poly-traumatized with 1 patient having sustained bilateral femur fractures. Thirty-two fractures were the result of motor vehicle collision, with incidents involving either an all terrain vehicle or dirt bike comprising 19 of these fractures. Mechanism of injury and associated fracture frequency data are compiled in Table 1.

Of the 65 fractures, 5 were open. Mean femoral shortening prior to application of traction was 3.2 ± 1.6 cm. Fracture location and pattern are represented in Figure 2, while grading of comminution is depicted in Figure 3. Mean hospital length of stay was 5.0 ± 6.3 days. In patients who sustained isolated femur fractures, mean length of stay was 2.4 ± 1.0 days. All 5 patients who required blood transfusions during their hospitalization were poly-traumatized, including 2 patients with splenic lacerations requiring splenectomy. No patient developed fat embolism, or VTE. No clinically significant neurological deficits were documented. A single poly-traumatized patient had an ipsilateral foot drop which persisted at the time of final follow-up. This patients' foot drop was secondary to a lumbosacral plexopathy, which was documented at the time of injury prior to femoral fracture fixation. One patient had an ipsilateral traumatic below knee amputation.

All included patients had clinical follow-up at 1 year. Forty-nine of 64 patients were assessed in clinical follow-up at 2 years. Patients had a mean radiographic follow-up period of 27.4 ± 8.1 months (range, 12–71 months). All patients had follow-up imaging obtained at a minimum 1 year following IM nail fixation. Fifty of 64 patients had imaging obtained at a minimum 2 years following IM nail fixation, with 21 patients having had imaging obtained greater than 3 years from the date of surgery. All patients achieved union, at a mean of 8.1 ± 1.3 weeks. No patient developed malunion or nonunion. No patient sustained superficial or deep surgical site infection. Twenty-two patients reported postoperative pain. Of these patients, 19 reported knee pain. A single patient reported a laterally based ipsilateral hip pain, proximal to the greater trochanter. This patient was one of 2 patients who developed heterotopic ossification within the abductor mass just proximal to the site of nail insertion. This patient was managed operatively with nail removal and surgical excision of HO following maturation. A second patient who developed HO had sustained a closed head injury at the time of femur fracture. This patient was asymptomatic, requiring no

**Table 1**

**Mechanism of injury and associated fracture frequency (n = 65).**

| Mechanism | |
|---|---|
| Motor vehicle collision | |
| All-terrain vehicle/dirt bike | 19 |
| Passenger in vehicle | 12 |
| Pedestrian struck by vehicle | 3 |
| Winter sports | |
| Hockey | 5 |
| Snowboarding | 4 |
| Tobogganing | 1 |
| Other activities | |
| Horseback riding | 7 |
| Bicycling | 5 |
| Trampolining | 2 |
| Skateboarding | 2 |
| Fall from height | 5 |

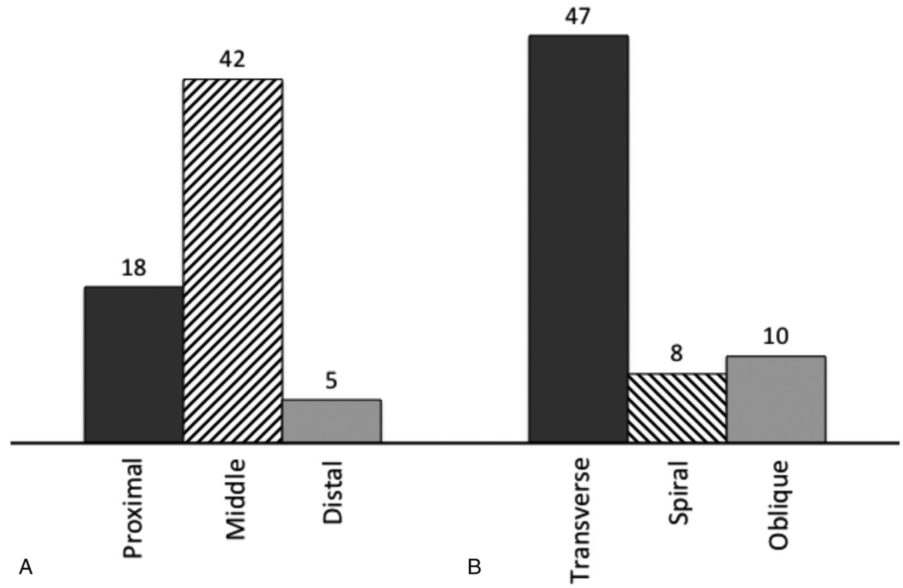


**Figure 2.** Diaphyseal location (A), and pattern (B) of pediatric femoral fractures treated with rigid IM nail fixation.

treatment. A total of 24 patients (36.9%) underwent reoperation. Fifteen patients underwent isolated distal locking screw removals. Nine patients underwent nail removal. No complications occurred in any of the 24 patients during or after reoperation.

At final clinical follow-up, no patient was requiring analgesic medication. No patient had a clinically significant limp. Examination of rotation, and leg lengths revealed all patients to have symmetric clinical rotation when compared with the contralateral side, and leg lengths within 2 cm. Review of final radiographs revealed no evidence of femoral head osteonecrosis in any of the 64 patients included in the study. Given the 2 cases of HO, a complication rate of 3.1% was observed following IM nail fixation of 65 traumatic diaphyseal femur fractures through the GT, in the skeletally immature.

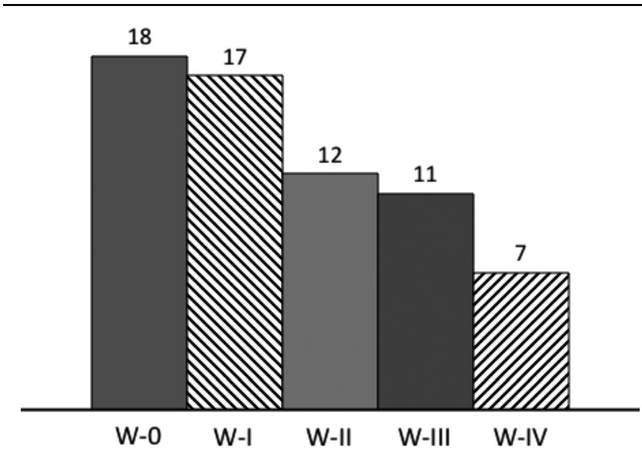


**Figure 3.** Gradation of fracture comminution using a modified Winquist classification. Winquist 0 (W-0)—no fragmentation at fracture site; Winquist I (W-I)—fragmentation involves less than 25% of the diaphyseal width; Winquist II (W-II) 25% to <50%); Winquist III (W-III) 50% to <75%; WInquist IV (W-IV) 75%–100% or segmental.

## 4. Discussion

Traumatic diaphyseal femur fractures in the skeletally immature are associated with significant morbidity, and may be treated successfully with both nonoperative and operative modalities. Fracture management decisions are made based largely on the age and weight of the patient as well as fracture characteristics.[6] Rigid IM nailing offers advantages including early mobilization, decreased joint stiffness, an expedited return to activity, decreased length of hospital stay, and a reduction in the overall cost of fracture care.[11] The intent of the present investigation was to determine the incidence of complications associated with anterograde rigid IM nailing of traumatic diaphyseal femur fractures through the GT in the skeletally immature. This is the second largest series reporting results of rigid IM nailing of diaphyseal femur fractures with a greater trochanteric start point in skeletally immature patients to date.[12]

Operative management of diaphyseal femoral fracture, when compared with nonoperative management, is associated with decreased rates of malunion, and fewer total adverse events including infection, reoperation, refracture, and LLD.[13] Current AAOS guidelines state that for any patient with diaphyseal femur fracture greater than 11 years of age, flexible IM nailing, rigid IM nailing, and submuscular plating may all be considered treatment options. Flexible IM nailing is a technique best utilized in "school-age" patients with "length stable" fractures (i.e., Winquist grade II or less). It is not suitable for proximal or distal femoral fractures as Flynn et al[14] reported a 66.7% failure rate of flexible titanium nails used in such fractures. A number of studies have shown favorable results with titianium elastic nails utilized in stable, mid-diaphyseal femoral fractures in patients aged 5 to 11 years.[15–17] However, poor clinical outcomes have been reported with the use of titanium elastic nails in patients weighing greater than 49 kg.[16,17] Additionally, flexible IM nail fixation can be associated with significant rotational malunion (>15 degrees), with rates between 10%[15] and 47%[18] reported in the literature. "Length unstable" (i.e., Winquist grade III or IV) fractures may best be treated with either rigid IM nail fixation or submuscular bridge plating. Submuscular plating can offer stability with complex fracture patterns not amenable to flexible nailing, and provides the benefit of avoidance of growth plates and preservation of proximal femoral blood supply. Favorable results have been published with treatment of unstable femur fractures treated with submuscular bridge plating.[19,20] Disadvantages of this modality include that it is more technically demanding to perform when compared with rigid IM nail fixation, and plate and screw removal can be lengthier, more difficult, and involve increased soft tissue trauma when compared with IM nail removal. Additionally, larger incisions are required with subsequent scarring. Further, and perhaps most importantly, patients who undergo submuscular bridge plating are not routinely permitted to weight bear for 6 to 8 weeks postoperatively,[21] whereas those undergoing rigid nail fixation are able to immediately weight-bear as tolerated. This is of particular significance in the setting of a poly-traumatized patient with contralateral lower limb injuries who may otherwise be unable to ambulate. Our center preferentially utilizes rigid IM nail fixation for length unstable femoral fractures with favorable clinical and radiographic results (Fig. 4).

In 1984, Winquist et al reported on 30 rigid IM nail implantations in 28 patients, who ranged in age from 10 years 10 months to 15 years 7 months. No patient developed femoral head osteonecrosis. Thereafter, several studies[11,22,23] were published of rigid IM nailing through the piriformis fossa in patients ranging from 10 to 16 years of age with no reported cases of femoral head osteonecrosis. In 1994, Beaty et al[24] reported a case of femoral head osteonecrosis in a female who underwent intramedullary nailing through the piriformis fossa at 11 years 6 months of age. Femoral head osteonecrosis was apparent 15 months after surgery. A number of case reports soon followed of femoral head osteonecrosis in the pediatric population with rigid IM nailing through the piriformis fossa.[25–27] Osteonecrosis in these cases is believed to be due to the open capital femoral physis


**Figure 4.** Length unstable (Winquist grade III) proximal femoral diaphyseal fracture in an 11-year-old male (A). Fracture appearance 1 year following rigid IM nail fixation through the LGT (B).

serving as a barrier to blood flow from the metaphysis to the femoral head.[8] The primary blood supply to the femoral head comes from the medial femoral circumflex artery, and injury to branches of this artery as they pass just posterior and medial to the piriformis fossa is believed causative.[8,28] This has led to widespread abandonment of IM nailing through the piriformis fossa. Some have advocated IM nailing through the tip of the trochanter,[29,30] while more recently a lateral trochanteric start point has been proposed.[31,32] In this series, both the TGT and LGT were used, and start point was dependent upon the nail used for fixation. Specifically, a TGT start point was used in fractures managed with a TAN (10 fractures), and a LGT start point was utilized in fractures fixated with an Adolescent TAN (55 fractures).

Rigid IM nailing through the TGT was described in 1970 by Mueller et al[33] and again by Winquist et al[10] in 1980. The technique was used to avoid fracturing the femoral neck, to prevent intracapsular contamination and potential subsequent septic arthritis of the hip, and to prevent damage to the blood supply to the femoral head with resultant osteonecrosis. Townsend and Hoffinger reported results of IM nail fixation through the TGT in 34 patients who ranged in age from 10 years 2 months to 17 years 6 months with a minimum follow-up of 2 years for 20 patients who had open physes. They reported no infections, nonunions, rotational deformities or implant failures, and no patient developed osteonecrosis of the femoral head. These results, although promising, were tempered by reports describing proximal femoral valgus and femoral neck narrowing with IM nailing through the greater trochanter.[34,35] Momberger et al reported results of IM nailing through the TGT in 48 patients aged between 10 and 16 years of age with follow-up in patients with open physes up to 60 months. No patient developed any significant alterations in the proximal femoral anatomy or osteonecrosis of the femoral head. Gordon et al[36] looked specifically for proximal femoral changes in skeletally immature patients after antegrade IM nailing. They concluded that for patients older than 9 years of age, IM nailing does not alter proximal femoral anatomy. Kanellopoulos et al also studied the effect of IM nailing on proximal femoral anatomy. Twenty patients with a mean age of 14 years were followed for 29 months after treatment with an IM nail with a TGT start point. All fractures healed clinically and radiographically by an average of 9 weeks. There were no significant differences in mean femoral length difference, mean neck-shaft angle, or mean femoral neck width. No patient developed a significant LLD, coxa valga, or femoral head osteonecrosis. Hammouda et al[37] published a series of 31 femurs in 28 patients who underwent femoral lengthening with a telescopic nail inserted through the TGT. No patient developed osteonecrosis or proximal femoral deformity. In 2014, Crosby et al[12] published the largest retrospective review of IM nailing of traumatic femur fractures in the skeletally immature. This study included 246 fractures managed over a 23-year period with a mean follow-up of 16 months. A complication rate of 9.8% (24 complications) was reported, with 2 cases (2.2%) of proximal femoral growth disturbance (coxa valga). No cases of femoral head osteonecrosis were reported. Results of the aforementioned studies when interpreted in conjunction with those of the present study suggest that using the GT as an entry point to the femoral canal respects the growing proximal femur and its vascular anatomy such that antegrade rigid IM nailing can be safely used in the adolescent patient population with diaphyseal femur fractures.

Systematic review of the literature[9] revealed rates of femoral head osteonecrosis of 2% (5 cases in 239 patients) with rigid IM nailing through the piriformis fossa and 1.4% (2 cases in 139 patients) with rigid IM nailing through the TGT. Zero cases were reported in 80 patients receiving IM nails through the lateral aspect of the greater trochanter. The 2 reported cases of femoral head osteonecrosis in patients who were treated with IM nail insertion through the TGT[38,39] have clearly debatable etiology. Stans et al[38] report a case of osteonecrosis in an 11-year-old girl 6 months after antegrade rigid IM nail fixation. Radiographs from the publication reveal a straight, large diameter IM nail which despite its purported TGT start point would have by virtue of nail diameter alone encroached upon the piriformis fossa. This may not represent an outcome secondary to IM nail insertion through the TGT, rather it may serve to provide further evidence of the potential for disruption of blood flow to the femoral head and resultant osteonecrosis with a piriformis fossa start point. Skak et al[39] reported a single case of hip osteoarthitis in a 33-year-old male who underwent IM nail fixation of a traumatic femur fracture through the TGT at age 15. The nail was removed 1 year following fracture fixation. The resultant hip osteoarthritis may have been secondary to the IM nail insertion, or perhaps nail removal. It is possible that any number of factors may have contributed to the development of hip osteoarthritis in the 17 years following placement of the IM nail through the TGT. The current series reports 0 cases of osteonecrosis following the rigid IM nailing of 65 fractures through both the TGT and the LGT in skeletally immature patients. This would suggest relative safety and efficacy of this treatment.

Limitations of the current investigation are those inherent to its retrospective design. As such, alterations of proximal femoral anatomy following IM nail fixation could not be assessed, as few patients had pelvic imaging available for evaluation at the time of injury as well as at final follow-up.

In conclusion, the results of the present study indicate that IM nailing of diaphyseal femur fractures through a trochanteric start point in skeletally immature patients can be both safe and efficacious. A complication rate of just 3.1% was observed in this series. No patient developed infection, malunion, nonunion, refracture, VTE, or significant LLD. No femoral head osteonecrosis was observed. Future investigations will aim to evaluate both functional outcomes and provide a comparative analysis of outcomes in skeletally immature patients treated with rigid versus flexible nails for traumatic diaphyseal femur fractures.

## References


1. McCartney D, Hinton A, Heinrich SD. Operative stabilization of pediatric femur fractures. Orthop Clin North Am. 1994;25:635–650.
2. Sahlin Y. Occurrence of fractures in a defined population: a 1-year study. Injury. 1990;21:158–160.
3. Hinton RY, Lincoln A, Crockett MM, et al. Fractures of the femoral shaft in children. Incidence, mechanisms, and sociodemographic risk factors. J Bone Joint Surg Am. 1999;81:500–509.
4. Hansen ST, Winquist RA. Closed intramedullary nailing of the femur. Kuntscher technique with reaming. Clin Orthop Relat Res. 1979;56–61.
5. Kempf I, Grosse A, Beck G. Closed locked intramedullary nailing. Its application to comminuted fractures of the femur. J Bone Joint Surg Am. 1985;67:709–720.
6. Kocher MS, Sink EL, Blasier RD, et al. Treatment of pediatric diaphyseal femur fractures. J Am Acad Orthop Surg. 2009;17:718–725.
7. Gautier E, Ganz K, Krugel N, et al. Anatomy of the medial femoral circumflex artery and its surgical implications. J Bone Joint Surg Br. 2000;82:679–683.
8. Trueta J. The normal vascular anatomy of the human femoral head during growth. J Bone Joint Surg Br. 1957;39-B:358–394.
9. MacNeil JA, Francis A, El-Hawary R. A systematic review of rigid, locked, intramedullary nail insertion sites and avascular necrosis of the femoral head in the skeletally immature. J Pediatr Orthop. 2011;31:377–380.
10. Winquist RA, Hansen STJr. Comminuted fractures of the femoral shaft treated by intramedullary nailing. Orthop Clin North Am. 1980;11:633–648.
11. Galpin RD, Willis RB, Sabano N. Intramedullary nailing of pediatric femoral fractures. J Pediatr Orthop. 1994;14:184–189.
12. Crosby SNJr, Kim EJ, Koehler DM, et al. Twenty-year experience with rigid intramedullary nailing of femoral shaft fractures in skeletally immature patients. J Bone Joint Surg Am. 2014;96:1080–1089.
13. Poolman RW, Kocher MS, Bhandari M. Pediatric femoral fractures: a systematic review of 2422 cases. J Orthop Trauma. 2006;20:648–654.
14. Flynn JM, Hresko T, Reynolds RA, et al. Titanium elastic nails for pediatric femur fractures: a multicenter study of early results with analysis of complications. J Pediatr Orthop. 2001;21:4–8.
15. Narayanan UG, Hyman JE, Wainwright AM, et al. Complications of elastic stable intramedullary nail fixation of pediatric femoral fractures, and how to avoid them. J Pediatr Orthop. 2004;24:363–369.
16. Moroz LA, Launay F, Kocher MS, et al. Titanium elastic nailing of fractures of the femur in children. Predictors of complications and poor outcome. J Bone Joint Surg Br. 2006;88:1361–1366.
17. Luhmann SJ, Schootman M, Schoenecker PL, et al. Complications of titanium elastic nails for pediatric femoral shaft fractures. J Pediatr Orthop. 2003;23:443–447.
18. Salem KH, Keppler P. Limb geometry after elastic stable nailing for pediatric femoral fractures. J Bone Joint Surg Am. 2010;92:1409–1417.
19. Hedequist D, Bishop J, Hresko T. Locking plate fixation for pediatric femur fractures. J Pediatr Orthop. 2008;28:6–9.
20. Sink EL, Hedequist D, Morgan SJ, et al. Results and technique of unstable pediatric femoral fractures treated with submuscular bridge plating. J Pediatr Orthop. 2006;26:177–181.
21. Li Y, Hedequist DJ. Submuscular plating of pediatric femur fracture. J Am Acad Orthop Surg. 2012;20:596–603.
22. Herndon WA, Mahnken RF, Yngve DA, et al. Management of femoral shaft fractures in the adolescent. J Pediatr Orthop. 1989;9:29–32.
23. Timmerman LA, Rab GT. Intramedullary nailing of femoral shaft fractures in adolescents. J Orthop Trauma. 1993;7:331–337.
24. Beaty JH, Austin SM, Warner WC, et al. Interlocking intramedullary nailing of femoral-shaft fractures in adolescents: preliminary results and complications. J Pediatr Orthop. 1994;14:178–183.
25. Buford DJr, Christensen K, Weatherall P. Intramedullary nailing of femoral fractures in adolescents. Clin Orthop Relat Res. 1998;85–89.
26. Mileski RA, Garvin KL, Crosby LA. Avascular necrosis of the femoral head in an adolescent following intramedullary nailing of the femur. A case report. J Bone Joint Surg Am. 1994;76:1706–1708.
27. O'Malley DE, Mazur JM, Cummings RJ. Femoral head avascular necrosis associated with intramedullary nailing in an adolescent. J Pediatr Orthop. 1995;15:21–23.
28. Chung SM. The arterial supply of the developing proximal end of the human femur. J Bone Joint Surg Am. 1976;58:961–970.
29. Momberger N, Stevens P, Smith J, et al. Intramedullary nailing of femoral fractures in adolescents. J Pediatr Orthop. 2000;20:482–484.
30. Townsend DR, Hoffinger S. Intramedullary nailing of femoral shaft fractures in children via the trochanter tip. Clin Orthop Relat Res. 2000;113–118.
31. Keeler KA, Dart B, Luhmann SJ, et al. Antegrade intramedullary nailing of pediatric femoral fractures using an interlocking pediatric femoral nail and a lateral trochanteric entry point. J Pediatr Orthop. 2009;29:345–351.
32. Gordon JE, Khanna N, Luhmann SJ, et al. Intramedullary nailing of femoral fractures in children through the lateral aspect of the greater trochanter using a modified rigid humeral intramedullary nail: preliminary results of a new technique in 15 children. J Orthop Trauma. 2004;18:416–422.
33. Mueller MAMWH. Manual of Internal Fixation. New York: Springer Verlag; 1970.
34. Gonzalez-Herranz P, Burgos-Flores J, Rapariz JM, et al. Intramedullary nailing of the femur in children. Effects on its proximal end. J Bone Joint Surg Br. 1995;77:262–266.
35. Raney EM, Ogden JA, Grogan DP. Premature greater trochanteric epiphysiodesis secondary to intramedullary femoral rodding. J Pediatr Orthop. 1993;13:516–520.
36. Gordon JE, Swenning TA, Burd TA, et al. Proximal femoral radiographic changes after lateral transtrochanteric intramedullary nail placement in children. J Bone Joint Surg Am. 2003;85-A:1295–1301.
37. Hammouda AI, Jauregui JJ, Gesheff MG, et al. Trochanteric entry for femoral lengthening nails in children: is it safe? J Pediatr Orthop. 2017;37:258–264.
38. Stans AA, Morrissy RT, Renwick SE. Femoral shaft fracture treatment in patients age 6 to 16 years. J Pediatric Orthop. 1999;19:222–228.
39. Skak SV, Overgaard S, Nielsen JD, et al. Internal fixation of femoral shaft fractures in children and adolescents: a ten- to twenty-one-year follow-up of 52 fractures. J Pediatr Orthop Part B Summer. 1996;5:195–199.