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Elastic stabile intramedullary nailing (ESIN) of diaphyseal femur fractures in children and adolescents

A strobe-compliant study

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Abstract

Elastic stabile intramedullary nailing (ESIN) is a well-established method to stabilize diaphyseal fracture of the femur (DFF) in children. We aimed to evaluate the minimal medullary canal diameter (MMCD) of the fractured femur relative to the diameter of the nails. We also analyzed the real anteversion angle (AVA) of the affected femur in comparison to the healthy femur.

We retrospectively reviewed the medical records and plain X-ray images of children aged 2–15 years treated with ESIN for unstable femoral shaft fractures between 2004 and 2012. We measured MMCD on preoperative plain X-ray images. Nail diameter (ND) and any postoperative complications were extracted from the medical records. At follow-up conducted at a median of 40 months (range: 4–103 months) after the operation, we obtained Dunn X-ray images of both hips. Particular emphasis was placed on postoperative torsional differences in relation to age, weight, and maturity of the growth plate.

We analyzed the relationship between postoperative rotational malalignment and the ratio of ND to MMCD.

Median age of the 22 children at the time of injury was 7.5 years (range: 2–15 years). Median body weight was 25 kg (range: 13–57 kg). Median MMCD amounted to 8.6 mm (range: 5.5–11.0 mm). Median ND/MMCD was 36.9% (range: 27.3%–47.4%). Radiological analyses revealed a median of 27.0° (range: −22.0° to +49.0°) of real AVA in the affected leg and 32.5° (range: 18.0°–48.0°) in the healthy leg.

Three children (13.6%) experienced a grade III complication (Clavien–Dindo classification of surgical complications; CDCSC). Two of these children suffered retrotorsion of the femoral neck, while the third child experienced diminished anteversion.

Overall, 3 of 22 children (13.6%) suffered a CDCSC-grade III complication (i.e., retrotorsion of the femoral neck in two children and diminished anteversion of the femoral neck in one child). We recommend obtaining Dunn images at the end of the operation to confirm correct rotational alignment after stabilization with ESIN. Further prospective studies are required to confirm our findings.

Abbreviations: AVA = Anteversion angle, CCD = Caput-collum-diaphysis angle, CDCSC = Clavien–Dindo classification of surgical complications, DFF = Diaphyseal fracture of the femur, ESIN = Elastic stable intramedullary nailing, MMCD = Minimal medullary canal diameter, ND = Nail diameter, ND/MMCD = Ratio of nail diameter to minimal medullary canal diameter.

Keywords: child, elastic stable, femur fracture, follow-up results, intramedullary nail, outcome, rotational malalignment

1. Introduction

Diaphyseal fractures of the femur (DFF) are common long-bone injuries in children and adolescents. DFF represent 1.5% of fractures in childhood.[1,2] There is a bimodal age distribution with two peaks of incidence, that is, one in the toddler age group and one in adolescence. Boys suffer from DFF more often than girls.[3] Typical mechanisms of injury are related to age groups. In infants and toddlers, falls[3,4] and child abuse[4] are the main causes of DFF. In the age group of toddlers to school-age children, motor vehicle vs. pedestrian collisions and falls are described as main causes of DFF.[3,4] In adolescents, motor vehicle collisions and sports incidents represent the most frequent causes of injury.[4,23]

Treatment of DFF in children and adolescents has evolved from nonoperative intervention using spica cast and traction toward surgical stabilization during the last 30 years.[5,6] Orthopedic surgeons use different operative techniques for stabilization, such as elastic stable intramedullary nailing (ESIN), external fixation, antegrade reamed or unreamed interlocked intramedullary nailing, or plate fixation. In the 6–10-year age group of children who sustained traumatic femur fractures who were admitted to children's hospitals were treated with internal fixation more frequently compared to the group of children treated at other hospitals.[2]

Firica et al reported a series of 250 femur fractures in children stabilized by modified Ender nails,[7] and Ligier et al subsequently popularized ESIN[8] in children. The technique has become a widely applied and well-accepted method to stabilize DFF in

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children and adolescents.[9,10] This minimally invasive procedure protects the soft tissue and thus produces small and esthetically acceptable scars, in contrast to open reduction and plate fixation. Avoidance of growth-plate injuries and avascular necrosis of the femoral head, which have rarely been reported after interlocking antegrade nail fixation, represents an additional advantage.[11] Moreover, ESIN is associated with shorter immobilization and hospitalization periods when compared to traction and spica cast treatment,[8] thus resulting in shorter absence from school for the children.[12,13] In addition, Bueschensschuetz et al reported greater acceptance of ESIN by the patients and their families and lower overall costs compared to treatment by traction and spica cast immobilization.[14]

Green et al performed mechanical analyses of various NDs and numbers of nails for stabilization of unstable femoral shaft fractures in a synthetic bone model.[15] Their findings led to the recommendation of using NDs no larger than 40% of the MMCD.

Regarding initial fracture displacement, transverse, short oblique, and comminuted fractures are less stable than long oblique and spiral fractures. After stabilization by ESIN, shortening of femur fractures accompanied by backing out of distal nail ends occurs predominantly in long oblique, spiral, and comminuted fractures.

Flynn et al also recommended a diameter of each nail amounting to 40% of the narrowest inner diameter of the femoral diaphysis.[16]

Nevertheless, malalignment and torsional differences are major postoperative complications after ESIN stabilization of DFF in children and adolescents.[17,18] Rotational malalignment of DFF may lead to increased or diminished anteversion of the femoral neck. Diminished anteversion or even retroversion of the femoral neck may result in impingement and osteoarthritis of the hip joint later in life.[19,20] To avoid subsequent osteoarthritis, rotational corrective osteotomies are recommended (distally or proximally) to correct rotational malalignment.[21–23]

Our study aimed to investigate the clinical and radiological outcome of DFF in children and adolescents. We focused on postoperative torsional differences of the proximal femur. We examined whether there is a radiologically quantifiable difference in anteversion between the operated and nonoperated legs after ESIN. We investigated possible correlations between the difference in anteversion and other preoperative parameters such as age and body weight of the patient and functional state of the growth plate. In addition, we studied the potential relationship between postoperative rotational malalignment and ratio of nail diameter (ND) to MMCD (ND/MMCD).

2. Patients and methods

This was a retrospective cohort study from January 01, 2004, to August 01, 2012. Approval was obtained from the local ethics committee (reference number EKNZ: 158/13).

We analyzed the medical records and plain radiographs of 47 consecutive children (aged between 2 and 15 years) who had sustained unilateral femoral shaft fractures and were stabilized with ESIN. For inclusion, the patients had to have a follow-up interval of at least 4 months.

Exclusion criteria comprised pathological fractures, cerebral palsy, spina bifida, or other neuromuscular conditions. We also excluded children initially managed by other institutions who were referred to us for further treatment. Overall, 7 children (14.9%) were excluded because they met one or several exclusion criteria.

Table 1

Demographics of patients followed up ($n=22$).

Case	Sex	Age in years	Weight in kg	Fracture side	Fracture type
1	M	10	30	L	Transverse
2	M	8	24	R	Spiral
3	M	10.5	57	R	Comminuted
4	M	13	45	L	Comminuted
5	M	3.5	21	L	Transverse
6	F	13	51	R	Transverse
7	M	2.5	16	L	Oblique
8	M	10	41	L	Spiral
9	F	3.5	14	L	Transverse
10	M	2.5	17	L	Oblique
11	M	2.5	13	R	Transverse
12	M	7	20	R	Spiral
13	M	6	25	L	Transverse
14	M	10.5	29	R	Spiral
15	F	5	20	L	Transverse
16	F	6	25	L	Spiral
17	F	11	53	L	Comminuted
18	F	13	45	L	Spiral
19	M	2	15	L	Oblique
20	M	5.5	18	L	Transverse
21	F	9	40	R	Comminuted
22	F	15	45	L	Transverse

All operations were performed under supervision of a certified pediatric orthopedic surgeon or pediatric surgeon.

Of the 40 study participants, 18 children (38.3%) were lost to follow-up. Thus, we included 22 patients in our study. After the injury, all patients were admitted to the emergency department. Anteroposterior (AP) and lateral radiographs were obtained for initial diagnosis.

Patient demographics consisting of age, sex, weight, and location and type of the fracture were recorded (Table 1). In 21 of 22 children, two retrograde ESIN nails had been inserted. In one patient, DFF was stabilized with three ESIN nails due to insufficient stability after insertion of two 3.5 mm intramedullary nails.

2.1. Surgical technique

All patients underwent general anesthesia and were placed in supine position. In 9 children (40.9%), a fracture table was used due to the surgeon's preference. All patients obtained a single-shot dose of cefazolin (12.5 mg/kg) administered intravenously 30–60 minute before skin incision.

Preoperatively, the medullary canal was measured on the AP radiograph to determine the correct ND. Isthmus of the femur diaphysis was defined visually. We measured the minimal width of the medullary canal by determining the distance between the two inner cortices by drawing a line at a right angle to the main axis of the femur diaphysis (Fig. 1). Both legs were disinfected for comparison of rotation and axis of the legs. Skin incisions (2–3 cm long) were made laterally and medially of the distal metaphysis of the fractured femur. Insertion points of the titanium intramedullary nails were placed 2–2.5 cm proximally of the distal femoral growth plate.

Two nails of the same diameter were used. The nails were prebent such that the apex of the convexity was at the level of the fracture. We inserted the intramedullary rods in a retrograde fashion up to the level of the fracture line. Then, closed reduction, controlled by image-intensifier imaging, was performed. Subsequently, the intramedullary nails were advanced beyond the

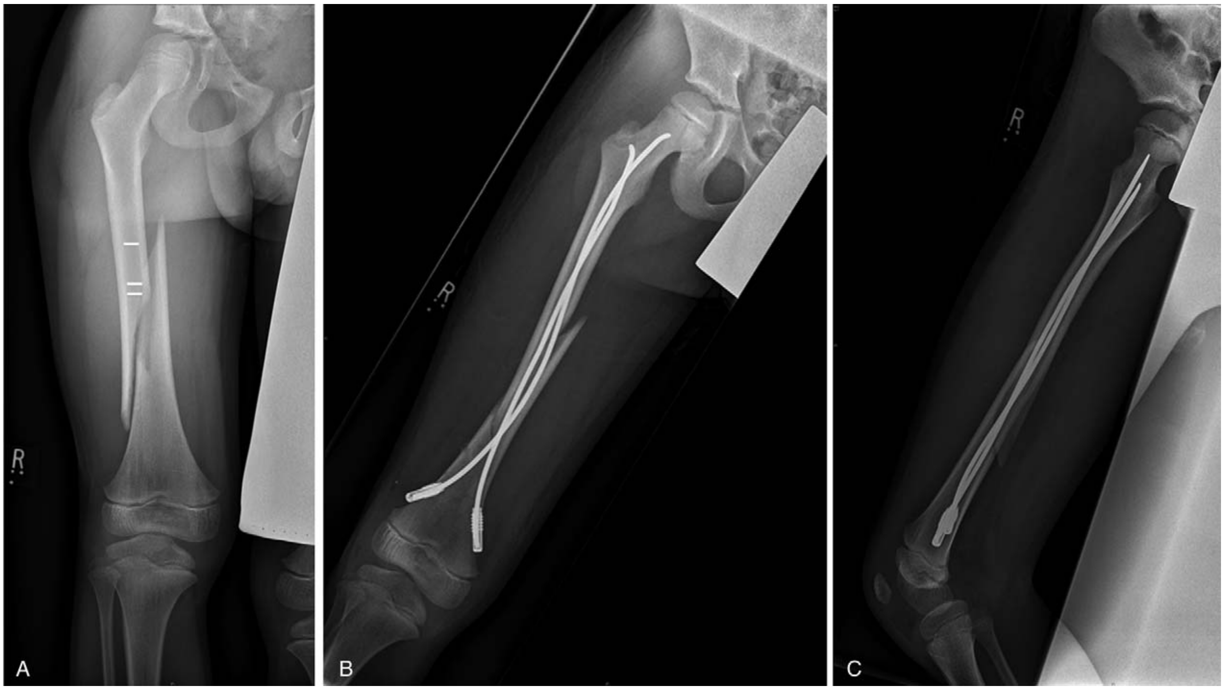

Figure 1. (A) Radiographic AP-image of fractured right femur (boy, aged 8 years). Three lines indicate region of narrowest inner diameter of medullary cavity. These lines are used for calculation of MMCD (patient 2). (B) Radiographic AP-image of fractured femur after stabilization with ESIN. There is 13° of residual valgus malalignment. EndCaps were applied to protect distal nail ends from backing out in this long oblique fracture. (C) Radiographic lateral image of femur fracture after stabilization with ESIN. Note slightly diminished anteversion of femoral neck and minimal recurvation of femoral shaft.

fracture line, and the tips of the nails were placed close to or within the femoral neck (medial nail) and greater trochanter (lateral nail).

The distal end of the nail was bent away from the cortex and shortened such that the nail end protruded over the bone surface for at least 1 cm to facilitate later extraction of the nail. In children with long oblique, spiral, or comminuted fractures, the surgeons frequently applied EndCaps or interlocking screws to prevent backing out of the nail ends. At the end of the operation, we clinically compared the axes of both legs.

Postoperatively, the leg was positioned in a foam cushion with the patella placed upright (neutral position concerning rotation). Pain-adapted mobilization to full weight bearing was encouraged in the first 14 days after surgery.

2.2. Follow-up examinations

Standardized clinical and radiographic follow-up examinations were conducted up to the time point of implant removal. The patients were interviewed about pain or functional impairment in daily life and sports. Clinical internal and external rotation range of motion (ROM) of the hip joint was measured in 90° of flexion of the hip and knee. In addition, a follow-up examination at least 4 months after the operation was offered. Overall, 22 of the original 40 patients (55.0%) underwent the follow-up examination.

2.3. Radiographic evaluation

We used the initial AP and lateral radiographs to determine the type of fracture. The fractures were classified as transverse (>60°–90°), long oblique (0°–60°), spiral (0°–60°), or comminuted fractures, according to the angulation of the fracture line in relation to the axis of the femur diaphysis. A fracture was classified as comminuted if there were more than two fragments.

The functional state of the distal femoral growth plate was classified as open, in transition to closure, or closed.

The medullary canal diameter was measured on the AP radiograph (Fig. 1). For analysis and comparison, we used the scale of our radiology department software (Centricity Enterprise Web by GE Medical Systems Information Technologies; Glattbrugg, Switzerland).

We applied three lines connecting both inner cortices perpendicularly to the axis of the femoral shaft and measured the diameter of the medullary cavity at the narrowest shaft region. All measurements were supervised by a senior pediatric or orthopedic surgeon (JM, ER). The median value (range) was used for further analysis.

At follow-up, we obtained AP and lateral plain X-ray images of the fractured femur at the time of expected consolidation of the fracture, in accordance with the child's age. In addition to clinical evaluation of hip and knee ROM, Dunn projection of both hips was obtained for long-term follow-up in 21 patients.[24] In 2 of 22 children (9%), we conducted a rotational CT scan before elective osteotomy for derotation that was indicated because of clinically obvious, severe torsional malalignment.

We measured the caput-collum-diaphysis (CCD) angle on the AP radiographic image of the affected femur (Fig. 2). We used the angle meter of our radiology department software for analyses. The CCD angle was defined as the angle measured between the axis of the femoral shaft and the axis of the femoral neck. The projected CCD angle of the affected leg was assumed to be identical to the CCD angle of the healthy leg.

Figure 2. Radiographic AP-image of fractured right femur (patient 2). Lines are drawn for measurement of CCD.

The Dunn projection was used to determine the projected anteversion angle (AVA; Fig. 3). We drew a line in the central axis of the femoral neck and measured the angle to the baseline of the X-ray table. This angle was defined as the "projected AVA." This procedure was performed on the affected as well as the healthy femur. Values obtained were compared to the conversion table values published by Müller and Rippstein,[25] and the "real CCD angle" and "real AVA" were recorded for further analyses.

2.4. Nail and medullary canal diameters

The diameter of the nail involved was retrieved from the medical records and was measured on the AP radiographs. The ND was compared to the MMCD, and the ND/MMCD ratio was calculated (Table 2).

2.5. Complications

Complications were categorized into 5 groups, according to the "contracted form" of the "Clavien-Dindo classification of surgical complications" (CDCSC).[26]

2.6. Data analysis

We collected patients' data by reviewing the medical records and radiographs. All data were entered into a database using Microsoft Excel 2008 for Mac (Microsoft Corporation, Redmond, Washington, USA). We analyzed the data using a standard statistical software package (JMP version 10, SAS Institute, Cary, USA). A Shapiro–Wilk normality test was applied to verify whether the data met the assumption of a parametric test. Normally and nonnormally distributed continuous data were compared using *t*-test and Wilcoxon signed-rank test, respectively. Ordinal and nominal data were compared using Wilcoxon signed-rank test and Chi^2-Test or Fisher exact test. To measure the correlation (linear dependence) between these variables, we used Pearson correlation coefficient for normally distributed data and Spearman's rho coefficient for nonnormally distributed data.

A logistic regression model was used to determine potential association between the nominal and continuous data (fracture type and difference of anteversion of femur). A P-value $<.05$ was considered significant.

3. Results

3.1. Patient characteristics

We included 22 children (14 boys [63.6%], 8 girls [36.4%]) in our investigation. The median age at injury was 7.5 years (range: 2.0–15.0 years). Body weights at the time of injury ranged from 13.0 to 57.0 kg with a median of 25.0 kg.

In 15 children (68.2%), the left femur was fractured. One child (4.5%) sustained multiple traumas in a railway incident. One child (4.5%) sustained a Gustilo–Anderson type I open fracture.[27] We confirmed intact neurovascular status in all children before and after the operation.

3.2. Functional state of the growth plate at the time of injury

Overall, 18 growth plates (81.8%) were open, and 4 growth plates (18.2%) were classified as transitional. There were no fused growth plates.

Comparison of the complication rates in the group of children with open physes at the time of injury and the group of children with physes in transition to closure revealed no higher complication rate in the second group ($X^2=0.43$; $P=.14$).

3.3. Fracture type and surgical technique

We observed 9 transverse (40.9%), 6 spiral (27.3%), 4 comminuted (18.2%), and 3 long oblique (13.6%) fractures.

The rate of complications in the group of children who had sustained transverse fractures was similar to that in the group of children who had sustained spiral, long oblique, or comminuted fractures ($X^2=.0003$; $P=.99$). Similarly, the rate of postoperative complications in the group of children who had sustained

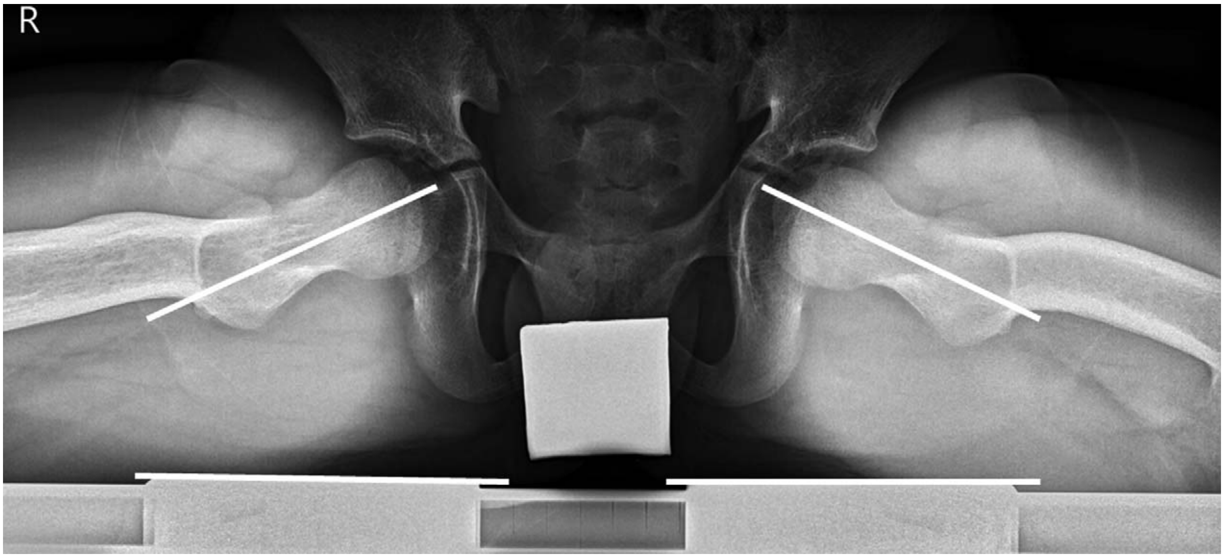

Figure 3. Dunn view with lines drawn for measurement of projected AVA (patient 2).

transverse or comminuted fractures did not differ significantly from the rate of postoperative complications in the group who had sustained long oblique or spiral fractures (X^2 = .0007; P = .99).

3.4. Nail diameter, endcaps, and interlocking screws

Table 2 shows the NDs of single nails in comparison to the real AVA. We observed an MMCD of 8.6 mm (range: 5.5–11.0 mm). The median ratio of ND of single nails to MMCD (ND/MMCD) was 36.9% (range: 27.3%–47.4%).

The categorized ND/MMCD ratio (0° to 39°; >40°) in the group of children who experienced complications did not differ significantly from that in the group of children who did not have any complications (X^2 = .69; P = .42). Similarly, the ND/MMCD ratio did not significantly correlate with the real AVA (r = −0.14; P = .42).

EndCaps (DePuy Synthes, Johnson & Johnson, Oberdorf, Switzerland) were applied to protect the distal nail end and to prevent the nail ends from backing out in 10 children (45.4%), and interlocking screws were used in 2 children (9.0%). The categorized rotational difference (≤10°, ≥11°) between the affected and unaffected femurs was comparable in the children treated with EndCaps or interlocking screws and those treated without such devices (X^2 = .44; P = .25). Moreover, postoperative complications in the group of children treated with ESIN equipped with EndCaps or interlocking screws were no more frequent than those in the group of children treated without these protective devices (X^2 = .077; P = .97).

We removed the implants after a median of 5.8 months (range: 1.9–9.0 months).

3.5. Complications

Seven children (31.2%) experienced an unfavorable event in the postoperative period up to the follow-up examination (Table 3). In 3 children (13.6%), a grade III (CDCSC) complication occurred, and 2 children (9.0%) suffered retrotorsion of the femoral neck. In these 2 children, real AVAs of 0.0° were measured in the first child and −22.0° in the second child. In a third child (4.5%), we observed a diminished anteversion of the femoral neck with a real AVA of 12.0° in the affected leg. We performed an internal-rotation osteotomy in 2 children (9.0%) to avoid subsequent impingement or osteoarthritis of the hip.

In 4 of the 22 children (18.0%), we noted a grade I (CDCSC) complication. Two of these children (9.0%) experienced reactive bursitis, one child (4.5%) suffered subcutaneous nerve irritation due to a protruding distal nail end, and one child (4.5%) experienced proximal cortical perforation of the nail end.

Table 2

Radiographic findings in patients followed up (n = 22).

	Nail			Real anteversion angle (AVA)	
Case	Nail size (mm)	MMCD (mm)	ND/MMCD ratio (%)	Affected leg (°)	Healthy leg (°)
1	3.5	8.6	40.7	37	29
2	3	8.7	34.5	27	33
3	4	10.4	38.4	35	26
4	3.5	9.5	36.9	27	27
5	3	8.4	35.7	13	32
6	3.5	9.2	38.2	12	33
7	2.5	7.7	32.6	27	43
8	3	8.3	36	25	36
9	2	5.5	36.6	48	41
10	2.5	7	35.7	40	40
11	2.5	6	41.7	42	47
12	3	8.2	36.6	24	30
13	3	6.6	47.4	36	28
14	3.5	8.7	40.1	49	48
15	3.5	9.25	37.9	30	42
16	3	11	27.3	16	27
17	4	10.9	36.8	0	23
18	2.5	10.7	37.4	−22	19
19	2	6.5	30.5	31	20
20	2.5	8	31.25	25	36
21	4	10.5	38.1	23	38
22	4	10.3	38.7	11	18

MMCD = minimal medullary canal diameter in mm, ND/MMCD = nail diameter/minimal medullary canal diameter ratio.

Table 3

Complications classified according to the Clavien-Dindo Classification of Surgical Classifications CDCSC.[28]

Case	Sex	Age in years	Weight in kg	CDCSC I	CDCSC III
1	M	10	30	Reactive bursitis	
6	F	13	51		Diminished anteversion
7	M	2.5	16	Reactive bursitis	
14	M	10.5	29	Cortical perforation by ESIN	
17	F	11	53		Retrotorsion
18	F	13	45		Retrotorsion
22	F	15	45	Subcutaneous nerve irritation	

3.6. Follow-up results

The median follow-up interval was 40.0 months (range: 4.0–103.0 months). In our mid-term follow-up examinations, we noted a 40.0° (median; range: 10.0°–80.0°) internal hip rotation of the affected leg. For the healthy hip, internal hip rotation amounted to 47.5° (median; range: 20.0°–90.0°). External hip rotation of the affected leg was 37.5° (median; range: 10.0°–80.0°), while the healthy side exhibited external hip rotation of 37.5° (median; range: 10.0°–55.0°).

There were no significant differences in the categorized groups of rotational differences (<10.0°; >11.0°) between the group of children with open femoral physes and those with physes in transition to closure ($X^2=.44$; $P=.52$).

We measured a median CCD angle of 140.0° (range: 130.0°–150.0°) on both the affected and healthy legs. The real AVA of the affected side showed a median of 27.0° (range: −22.0° to +49.0°). For the intact leg, a median real AVA of 32.5° (range: 18.0°–48.0°) was obtained. There was no significant correlation between age at injury and real AVA at follow-up ($r=.21$; $P=.30$). We noted no significant correlation between the weight of children at the time of injury and real AVA ($r=.35$; $P=.11$).

The categorized types of fractures (transverse vs. spiral, long oblique, and comminuted fractures) were similar in the group of children who experienced rotational differences of <10° and those who had rotational differences of >11° ($X^2=.057$; $P=.96$). Logistic regression revealed no association between the fracture type and rotational difference ($P=.75$).

Table 4 shows the outcomes classified according to the Titanium Elastic Stable Nails Outcome Scoring System.[16]

4. Discussion

In the last three decades, ESIN has become a well-accepted surgical technique to stabilize DFF in children aged between 6 and 12 years weighing less than 50 kg. The technique was initially described by Ender and Weidner[28] and Firica et al[7] and was subsequently popularized by French authors.[8,29] These authors claimed that ESIN provides minimally invasive, stable, safe, and efficient stabilization of DFF in children. In addition, they concluded that this type of osteosynthesis provides sufficient elastic rotational stability when treating long-bone shaft fractures of the weight-bearing lower extremities in children.

Various studies[16,30,31] focused on the benefits and complications of ESIN and concluded that this technique is a safe and effective method to stabilize DFF in children aged between 6 and 12 years. Some authors voiced concern that in children with greater body weight and adolescents; ESIN may not provide sufficient stability for DFF.[32,33] In a multicenter study, Moroz et al[32] noted a statistically significant relationship between age and outcome and a five times higher risk of a poor outcome in children weighing more than 49 kg. Ramseier et al[10] analyzed the outcomes of different surgical techniques such as ESIN, external fixation, rigid intramedullary nail fixation, and plate fixation in a retrospective cohort study of 194 DFF in 189 patients. The cohort included 105 adolescents aged 12–18 years with a mean body weight of 47.6 kg (up to 80 kg) treated with ESIN. The authors were unable to confirm the findings of Moroz et al who reported a significant association between the rate of complications and higher age and/or body weight.[34,35]

Rotational stability was investigated in depth by Gwyn et al[36] in various types of femoral fractures in a synthetic bone model of pediatric DFF. They concluded that "titanium elastic intramedullary nails provide a consistent means of controlling rotation in a variety of fracture patterns in a simulated bone model." The authors were, however, unable to investigate the role of the soft tissue and periostal sleeve regarding the torsional stiffness in their model.

In this retrospective cohort study, we investigated the surgical, radiological, and clinical mid-term outcomes in 22 pediatric patients with DFF who underwent ESIN between 2004 and 2012. We noted severe postoperative rotational malalignment in 3 of 22 children (13.6%) following stabilization of femoral shaft fractures with ESIN, which required derotational osteotomy.

We hypothesize that ESIN osteosynthesis provides limited stability in DFF in a subgroup of children. Thus, we focused on various aspects to find the causes of postoperative rotational displacement in our cohort. Three children with diminished anteversion or retroversion necessitating rotational osteotomy had a median age of 13.0 years and a median body weight of 51.0 kg, while the group of children who suffered minor complications or no complications had a median body weight of 25.0 kg and a median age of 7.5 years. We noted no significant correlation between the weight of patients at the time of injury and real AVA at follow-up ($r=.35$; $P=.11$). Similarly, no significant correlation between the age of patients and the real AVA at follow-up was apparent ($r=.21$; $P=.30$). Thus, we were unable to confirm the results published by Moroz et al, who reported poor outcome of

Table 4

Flynn Outcome Scores*.[16].

	n	%
Excellent result	6	27.3
Satisfactory result	10	45.5
Poor result	6	27.3

*A patient's score was defined by the category of the worst result.
The treatment results of ESIN applied for DFF is based on the 4 parameters: leg length discrepancy, malalignment, pain, and complications.

ESIN stabilization of DFF in older children and children weighing more than 49 kg.[34]

There is some controversy about the ideal diameter of intramedullary nails. In general, an ND of 40% of the MMCD is recommended.[16] Lascombes et al suggested that the ND/MMCD ratio plays an important role in torsional stiffness after ESIN.[37] From an investigation in 81 consecutive DFF treated with ESIN, Lascombes et al concluded that an ND of >40% of the medullary canal diameter was required to achieve a favorable outcome.[37,38]

In our cohort, we were unable to confirm a significant correlation between ND/MMCD and the occurrence of postoperative rotational malalignment. We hypothesize that there are three crucial steps in the ESIN management of DFF that may influence the occurrence of rotational malalignment. First, the surgeon may cause rotational malalignment by accepting an unsatisfactory reduction throughout surgery. Second, rotational malalignment may be induced postoperatively when positioning the injured leg in external rotation. Third, early weight bearing might play a role in promoting postoperative rotational malalignment. To the best of our knowledge, there is no prospective study addressing these questions, and thus it remains unknown whether our assumptions can be made responsible for postoperative rotational malalignment.

Concerning the first assumption, we hypothesize that special attention should be paid on restoring the anatomical leg axis and correct rotation of the fracture fragments during the operation. For this, both legs must be cleaned and draped so that the anatomical leg axes and rotation can be compared. For additional safeguarding, radiological imaging may be considered. We recommend to perform a Dunn–Rippstein view[24] to compare the AVA of the femoral neck of both the healthy and fractured legs and thus monitor symmetric leg rotation. By performing a correct Dunn–Rippstein view, intraoperative rotational malalignment can be detected and thus corrected during the same operation and anesthesia. A prerequisite for this procedure is a correctly obtained Dunn–Rippstein projection.[24] Intraoperatively, it is challenging to achieve the required angles (90° flexion in hip and knee, and 20° abduction in the hip) for both legs. Furthermore, positioning of the image intensifier may pose a challenge, and an additional X-ray dose would be required.

Concerning the second assumption, we suggest that after the operation the fractured leg should be positioned in a foam cushion with the patella placed upright (neutral position). External rotatory force on the recently stabilized fracture has to be avoided. Narayanan et al[31] pointed out the following:

"An external force applied to the fracture will cause the fracture to bend, translate, or rotate, but when the force is removed, the elastic nails will return (elastic recoil) the fracture to its stable reduced position, as long as any external force applied to the fracture (including body weight or weight bearing) does not exceed the elastic limit of the nails. The fixation is not rigid but sufficiently stable so that no additional external immobilization is required."

We hypothesize that leverage of the shank and foot positioned in external rotation while the patient lies in supine position could easily exceed the elastic limit of the ESIN osteosynthesis and may thus result in permanent rotational malalignment.

Regarding the third assumption, several authors mentioned a possible influence of high body weight on postoperative outcome although no consent has been reached.[10,34] There was no significant correlation between body weight and rotational malalignment (real AVA) in our cohort ($r=.35$; $P=.11$).

To counteract postoperative rotational forces at the site of the ESIN osteosynthesis, some authors recommended applying a hip spica cast to immobilize the hip and knee and limit displacing rotational forces.[16] Some authors postulated the use of a long leg cast with moderate flexion of the knee joint to keep the child from bearing weight on the injured leg.[16]

It is conceivable that mobilization with the use of crutches before fracture consolidation might induce torsional forces on the fracture site that exceed the elastic stability limit of ESIN implants. At our department, patients are encouraged to perform pain-adapted transition to full weight bearing in the first 14 days after surgery.

4.1. Study limitations and strengths

We conducted a retrospective study in a small number of patients. The median follow-up interval of 40 months is relatively short, and there was a high dropout rate (18 of 40 children; 38.3%). We observed a complication rate of 31.8%. It must also be kept in mind that we observed severe rotational malalignment in a small number of patients. In addition, the groups were too small for a well-powered analysis. These facts may have influenced the results of our investigation and prevented us from making any significant conclusions.

The advantages of our study were a clear study design to examine the hypothesis that poor outcomes after ESIN may be related to poor rotational alignment or poor control of reduction and stability. A significant difference of the AVA after DFF in children is a clinically relevant prognostic factor concerning the long-term well-being of patients.

In addition, this study may help to reduce medical costs in the future as it may influence the processes of DFF stabilization in children. In addition, our study may help to avoid development of posttraumatic impingement and osteoarthritis thus preventing more costly hospitalizations.

5. Conclusions

When stabilizing femoral shaft fractures with ESIN, the rate of complications in the group of children who had suffered transverse or comminuted fractures was similar to that in the group of children who had sustained spiral or long oblique fractures. Overall, 3 of 22 children (13.6%) suffered a CDCSC-grade III complication, with retrotorsion of the femoral neck occurring in 2 children and diminished anteversion of the femoral neck in 1 child. We therefore recommend obtaining intraoperative Dunn images at the end of the operation to confirm correct rotational alignment of the fracture fragments after stabilization with ESIN. Further prospective studies are required to confirm our findings.

Author contributions

BF, GdB, JM, and ER contributed substantially to the design, recruitment, survey, data collection, and evaluation of the study. BF and CC completed the data analyses and made substantial contribution to the interpretation of the data. CC performed the statistical analyses. BF and JM drafted the manuscript, which was critically reviewed by SH-C. All authors read and approved the final manuscript.

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