International Orthopaedics (2020) 44:129–139
https://doi.org/10.1007/s00264-019-04429-4

ORIGINAL PAPER

Initial displacement as a risk factor for avascular necrosis of the femoral head in pediatric femoral neck fractures: a review of one hundred eight cases

Wentao Wang[1] · Yiqiang Li[2] · Yueming Guo[3] · Ming Li[4] · Haibo Mei[5] · Jingfan Shao[6] · Zhu Xiong[7] · Jin Li[8] · Federico Canavese[9] · Shunyou Chen[1] · Chinese Multicenter Pediatric Orthopedic Study Group (CMPOS)

Received: 2 July 2019 / Accepted: 1 October 2019 / Published online: 26 October 2019

Abstract

Purpose To evaluate the correlation between avascular necrosis (AVN) and the amount (severity) and direction (translation and angulation) of initial displacement of pediatric femoral neck fractures.

Methods We retrospectively reviewed 108 pediatric patients (mean age 10.3 ± 4.1 years) with femoral neck fractures. The amount of initial translation (T) and angulation (A) was measured on anteroposterior (AP; T_{AP}% and A_{AP}) and lateral (T_L% and A_L) radiographs. The direction of translation was determined on AP (medial or lateral) and lateral radiographs (anterior or posterior). Furthermore, the presence of a comminuted medial cortex on the AP pelvis radiograph was also recorded. Logistic regression analysis, receiver operating characteristic (ROC) curve analysis, student's *t* tests, and chi-square tests were used to evaluate the correlation between AVN and the severity and direction of displacement.

Results Twenty-eight out of 108 hips (25.9%) developed AVN of the femoral head. Logistical regression analysis indicated that T_{AP}%, T_L%, A_{AP}, and A_L were risk factors for AVN ($P < 0.05$). The analysis of ROC curves found that T_{AP}% over 37.4% and T_L% over 29% were the cut-off values for an increased incidence of AVN; similarly, A_{AP} over 8° and A_L over 18.6° were the cut-off values for an increased incidence of AVN. The amount of initial translation is a better predictor of AVN than angulation is; fractures with posterior translation ($P = 0.002$) and/or medial comminution had a significantly higher incidence of AVN ($P = 0.005$). The mean diagnostic accuracy of translation (74–75%) was significantly higher than that of angulation (65–66%).

Conclusions Displacement severity and direction are important radiological parameters to be assessed in children with femoral neck fractures. Initial translation better predicts AVN than angulation does. Posterior translation and medial comminution are associated with an increased risk of AVN.

Keywords Femoral neck fracture · Children · Avascular necrosis · Femoral head · Initial displacement · Translation · Angulation

Wentao Wang, Yiqiang Li, Yueming Guo, Ming Li and Haibo Mei contributed equally to this work.

Level of Evidence: III

✉ Shunyou Chen
csy508@163.com

1 Department of Pediatric Orthopedics, FuZhou Second Hospital Affiliated to Xiamen University, 47th ShangTeng Road of CangShan District, FuZhou 350007, FuJian Province, China

2 Department of Pediatric Orthopedics, GuangZhou Women and Children's Medical Center, GuangZhou Medical University, GuangZhou, China

3 Department of Pediatric Orthopedics, Foshan Hospital of Traditional Chinese Medicine, Foshan, China

4 Department of Pediatric Orthopedics, Children's Hospital of Chongqing Medical University, Chongqing, China

5 Department of Pediatric Orthopedic, Hunan Children's Hospital, Changsha, Hunan, China

6 Department of Pediatric Orthopedics, TongJi Hospital of TongJi Medical College Huazhong University of Science and Technology, Wuhan, China

7 Department of Pediatric Orthopedics, ShenZhen Children's Hospital, Shenzhen, China

8 Department of Pediatric Orthopedics, Wuhan Union Hospital, Wuhan, China

9 Department of Pediatric Surgery, University Hospital Estaing, Clermont-Ferrand, France

Introduction

Pediatric femoral neck fractures are relatively rare (0.3 to 0.5% of all pediatric fractures), although they are frequently associated with complications [1–3]. The most common and disabling complication is avascular necrosis (AVN) of the femoral head, which directly results in long-term morbidity [4, 5].

Previous studies have reported several risk factors for AVN in children with femoral neck fracture, including age, fracture displacement, time to surgery, reduction method, and quality of reduction [4–6]. Although several reports have indicated the amount of initial displacement as an important, independent predictive factor for AVN in pediatric femoral neck fractures [4, 7, 8], other studies have reported different findings with conflicting results [9, 10]. This outcome may be attributed to the lack of adequate sample size (e.g., less than 70 patients in previous studies) and the inconsistent definition of displacement [4, 7–11]. Although a recent meta-analysis (6 articles and 230 patients) identified the amount of initial displacement as a risk factor for AVN, the heterogeneity among the different included studies contributed to a weakened conclusion of this research [8].

At present, most studies have evaluated the effect of displacement on the incidence of AVN by assessing fractures as "displaced" or "not displaced" [4, 7–10]. However, this method of evaluating displacement does not provide any information on the amount (severity) or the direction of displacement (translation and angulation). As a result, it is difficult to evaluate whether any correlation exists between the amount of initial displacement and the incidence of AVN in children sustaining proximal femur fractures.

In this multicenter investigation, we aimed to evaluate the potential correlation between the occurrence of AVN and the amount (severity) and direction (translation and angulation) of the initial displacement of pediatric femoral neck fractures.

Materials and methods

After securing Institutional Review Board (IRB) approval (approval no. 20190301), we retrospectively reviewed the medical records of 327 children with femoral neck fractures who were admitted from March 2010 to May 2017 to eight institutions. Detailed demographic and clinical data are shown in Table 1 (Table 1).

The inclusion criteria were as follows: 1) diagnosis of femoral neck fracture, 2) age less than 17 years at the time of injury, 3) reduction within 14 days of trauma, 4) follow-up duration longer than 12 months, 5) complete clinical and radiographic data, and 6) standard preoperative AP and cross-table or frog-leg lateral pelvic radiographs [11, 12]. Patients with a concomitant neuromuscular condition, pathological fracture, more than 14 days between the injury and the time of reduction, incomplete medical records and/or imaging data, or a follow-up of less than 12 months were excluded from the analysis.

A total of 108/327 patients (108 fractures; 38 females and 70 males) met the inclusion criteria (33%). The average age at the time of injury was 10.3 ± 4.1 years (range, 2 to 16), and the mean follow-up duration was 21.5 ± 13.0 months (range, 12 to 68). The mechanisms of injury included motor vehicle accident in 22 fractures (20.4%), falling from a height in 47 fractures (43.5%), sports-related injury in 32 fractures (29.6%), and other causes in 7 fractures (6.5%) (Table 1).

The remaining 219 patients (67%) were excluded due to concomitant diagnosis of pathological femoral fractures (7 patients, 2.1%), diagnosis of slipped capital femoral epiphysis (SCFE) (2 patients, 0.6%), more than 14 days between the injury and time of reduction (13 patients, 4.0%), follow-up less than 6 months (12 patients, 3.7%), incomplete clinical or radiographic data (54 patients, 16.5%), and the preoperative anteroposterior (AP) pelvis radiographs not allowing proper measurement of translation and angulation (131 patients, 40.1%).

Pediatric femoral neck fractures were classified according to the system described by Delbet and adapted by Colonna [13]. Eighty hips (74.1%) were type II (trans-cervical), and 28 hips (25.9%) were type III (cervico-trochanteric) fractures.

The amount and direction of initial fracture displacement (translation and angulation) were measured on AP and lateral pelvis radiographs.

Translation is the movement of the proximal and distal bone fragments away from each other; it is described using the width of the distal bone fragment as a context and expressed as a percentage. In particular, translation was measured on both AP (T_{AP}%) and lateral (T_L%) radiographs (Fig 1).

Angulation is the angle between the proximal and distal fragment and is expressed in degrees. In particular, angulation expresses the angle between the proximal and distal fracture lines on both AP (A_{AP}) and lateral (A_L) radiographs; the angle between the distal fracture line and the femoral shaft axis (AFF_{AP}) on AP radiographs was also measured (Fig. 1).

Additionally, the direction of translation was evaluated on both AP (no translation, medial translation, or lateral translation) and lateral radiographs (no translation, anterior translation, or posterior translation) (Fig. 2). Furthermore, the presence of a comminuted medial cortex on the AP pelvis radiograph was also recorded. Two experienced pediatric orthopedic surgeons (WWT and LYQ) measured these parameters independently, and their mean values were used in the statistical analysis.

All measurements were performed using the Picture Archiving and Communication Systems (PACS; GE, USA).

Sixty-one hips (56.5%) were treated through closed reduction and internal fixation (CRIF), and the other 47 hips (43.5%) underwent open reduction and internal fixation (ORIF). Eighty-eight fractures (81.5%) were managed by cannulated screw fixation, and the remaining 20 fractures (18.5%) underwent screw and plate fixation.

Table 1 Demographics of the patients among different hospitals

	FSHTCM	CHCQMU	FZSHXMU	HNCH	Others	Total
Patients (Hips)	43(43)	19(19)	17(17)	19(19)	10(10)	108(108)
Gender (Male/Female)	27/16	17/2	10/7	9/10	7/3	70/38
Age (months)	11.9 ± 3.6	10.7 ± 4.2	9.9 ± 3.2	8.4 ± 3.8	6.9 ± 4.6	10.3 ± 4.1
Laterality (L/R/B)	29/14/0	10/9/0	10/7/0	11/8/0	5/5/0	65/43/0
Mechanism of injury (TA/Fa/Sp/Ots)	10/19/12/2	5/8/5/1	3/6/6/2	2/10/5/2	2/4/4/0	22/47/32/7
Type of fracture (Delbet I/II/III/IV)	0/34/9/0	0/16/3/0	0/11/6/0	0/13/6/0	0/6/4/0	0/80/28/0
Time from trauma to reduction(days)	2.9 ± 1.0	4.8 ± 3.4	2.7 ± 1.7	1.5 ±0 .6	4.9 ± 3.5	3.1 ± 2.3
Reduction methods (CRIF/ORIF)	36/7	3/16	3/14	11/8	8/2	61/47
Fixation methods (K/S/P)	0/43/0	0/19/0	0/3/14	0/17/2	0/6/4/0	0/88/20
Reduction quality (An/Ac/Uac)	19/19/5	6/12/1	9/5/3	10/8/1	4/3/3	48/47/13
Follow up time(months)	23.0 ± 14.2	20.9 ± 10.6	19.4 ±1 1.0	18.4 ± 13.1	25.4 ± 14.7	21.5 ± 13.0
AVN (No/Yes)	30/13	13/6	14/3	16/3	7/3	80/28
AVN rate (%)	30.2	31.6	17.7	15.8	30.0	25.9

FSHTCM, Foshan Hospital of Traditional Chinese Medicine; *CHCQM*, Children's Hospital of Chongqing Medical University; *FZSHXMU*, Fuzhou Second Hospital Affiliated to Xiamen University; *HNCH*, Hunan Children's Hospitall; *Others*, including Wuhan Union Hospital, TongJi Hospital of TongJi Medical College of Huazhong University of Science and Technology, Guangzhou Women and Children's Medical Center, and Shenzhen Children's Hospital

L, left; *R*, right; *B*, bilateral

TA, traffic accident; *Fa*, fall; *Sp*, sports; *Ot*, others

CRIF, closed reduction and internal fixation; *ORIF*, open reduction and internal fixation

K, K-wire; *S*, screw; *P*, plate

An, anatomical; *Ac*, acceptable; *Uac*, unacceptable

According to Song's classification system [14], reduction quality was divided into three groups: 1) anatomical reduction, reduction with no displacement or angular deformity, 2) acceptable reduction, reduction with displacement of less than 2 mm or angular deformity within 20° of the normal neck-shaft angle, and 3) unacceptable reduction, reduction with displacement of more than 2 mm or angular deformity of more than 20° of the normal neck-shaft angle.

At the final follow-up visit, AVN of the femoral head was assessed on AP and lateral radiographs. The presence of AVN and the degree of vascular involvement according to Ratliff's classification [15] were evaluated by two independent raters who were not involved in the care of any of the patients (FC and CSY). If the raters could not come to an agreement, a discussion with at least three other senior pediatric orthopedic surgeons was performed.

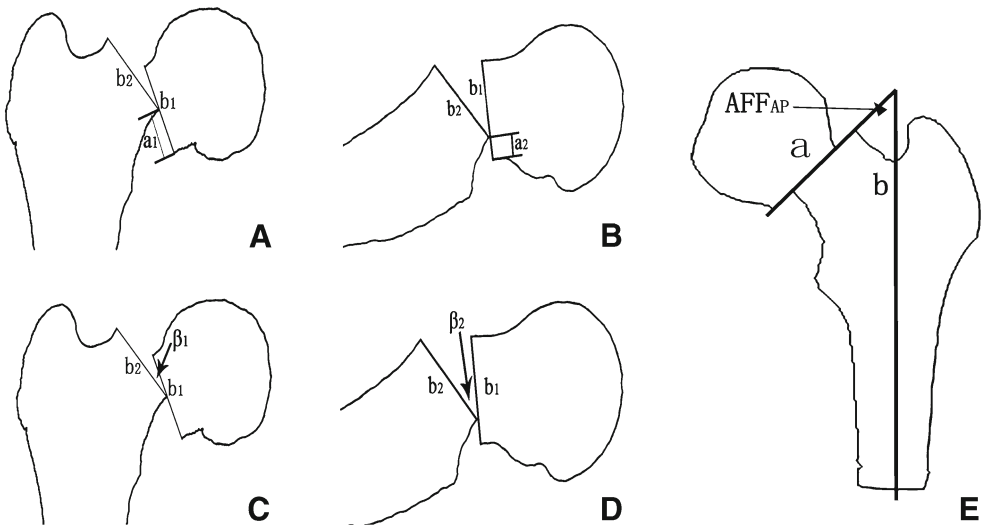

Fig. 1 Initial translation, expressed as a percentage, was measured on both AP (a1/b1*100%) (**A**) and lateral radiographs (a2/b1 100%) (**B**). The initial angulation (in degrees) between the proximal and distal fragments was assessed on both AP (β1) (**C**) and lateral radiographs (β2) (**D**). The angle (AFF_{AP}) was measured between the distal fracture line (line a) and the femoral shaft axis (line b) on the AP radiograph (**E**)

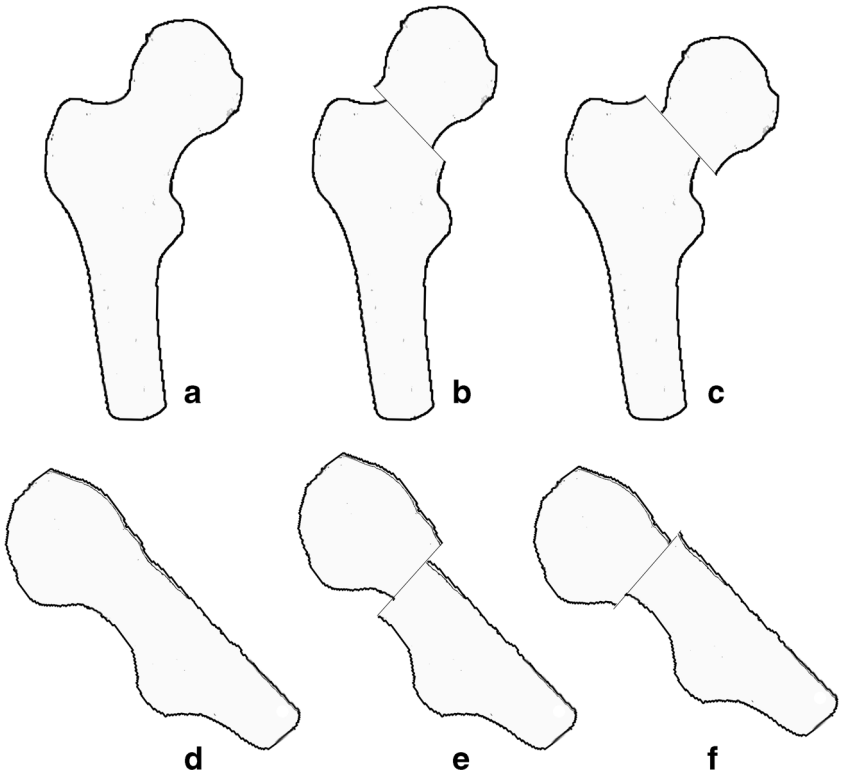

Fig. 2 The direction of translation was evaluated on both AP. (**a** No translation; **b** Medial translation; or **c** Lateral) and lateral radiographs (**d** No translation; **e** Anterior translation; or **f** Posterior translation)

Statistical analysis

Statistical analysis was performed using the statistics package SPSS 13.0 (SPSS, Chicago, IL, USA). The data are expressed as numerical variables and frequencies and percentages as the means and standard deviations. Spearman correlation analysis was used to evaluate the correlation of initial displacement with the type of fracture, reduction quality and degree of vascular involvement. Logistical regression analysis and Student's *t* tests were used to evaluate the correlation between the incidence of AVN and the amount of initial displacement (T_{AP}%, T_L%, A_{AP}, A_L, and AFF_{AP}) and the time to reduction. Then, receiver operating characteristic (ROC) curve analysis was used to determine the cut-off value and corresponding sensitivity, specificity, and diagnostic accuracy. Chi-square tests were used to assess the effect of displacement direction and comminuted fracture at the medial and posterior cortices and the time to reduction as well as the quality of reduction on the incidence of AVN. The level of statistical significance was set at $P < 0.05$.

Results

A total of 108 fractures were included. Anatomical reduction was achieved in 48 fractures (44.4%), acceptable reduction in 47 fractures (43.5%), and unacceptable reduction in 13 fractures (12%). The quality of reduction was similar among patients with AVN or without ($\chi^2 = 0.348$; $P = 0.863$). The mean time from trauma to treatment was 3.1 ± 2.3 days (range, 1 to 13). Fifteen fractures (13.9%) were treated within the first 24 h of trauma, 40 within 48 h (37%), 26 within 72 h (24.1%), 10 within 96 h (9.3%), and 11 fractures between 5 and 7 days from trauma (9.2%); only 7 fractures were treated more than 1 week after initial trauma (6.5%). However, the timing of fracture fixation in patients with AVN was similar to those without AVN ($t = 0.567$; $P = 0.572$). Moreover, the AVN rate in patients treated within 24 h from injury was comparable to those treated beyond 24 h (Fisher; $P = 0.755$).

Spearman's correlation analysis identified that the type of fracture positively correlated with T_{AP}% ($P = 0.019$) and T_L% ($P = 0.004$); no significant correlation between A_{AP}, A_L, and AFF_{AP} and the type of fracture was found ($P > 0.05$). However, patients with type III (21.4%) and type II fractures (27.5%) had similar AVN rate ($\chi^2 = 0.398$; $P = 0.528$). Additionally, Spearman's correlation analysis identified that the quality of reduction negatively correlated with T_{AP}%, T_L%, A_{AP}, and A_L ($P < 0.05$) (Table 2); no significant correlation between AFF_{AP} and the quality of fracture was found ($P = 0.722$).

Twenty-eight out of 108 hips (25.9%) developed AVN of the femoral head; according to Ratliff's classification, 10 hips (35.7%) were type I (total collapse of the epiphysis), and the remaining 18 hips (64.3%) were type II (minimal collapse of the epiphysis). Fisher's exact test did not show any significant difference among the included institutions ($P = 0.662$).

Logistical regression analysis indicated that T_{AP}%, T_L%, A_{AP}, and A_L were important risk factors for AVN ($P < 0.05$),

Table 2 Spearman's correlation analysis of initial displacement with quality of reduction

Initial displacement	Correlation coefficient	*P*
T_{AP} (%)	− 0.386	< 0.001#
T_L (%)	− 0.395	< 0.001#
A_{AP} (°)	− 0.275	0.004#
A_L (°)	− 0.253	0.008#
AFF_{AP} (°)	− 0.035	0.722

T_{AP}, percentage of translation related to distal fracture line on AP view of radiographs

T_L, percentage of translation related to distal fracture line on lateral view of radiographs

A_{AP}, the angle between the fracture lines on AP view of radiographs

A_L, the angle between the fracture lines on lateral view of radiographs

AFF_{AP}, the angle between the distal fracture line and the femoral shaft axis on AP view of radiographs

# $p < 0.05$

while AFF_{AP} was not a risk factor for AVN in children with proximal femur fractures (Table 3). Student's *t* tests also confirmed these findings (Table 4).Similarly, Spearman's correlation analysis indicated that the degree of vascular involvement positively correlated with T_{AP}%, T_L%, A_{AP}, and A_L ($P < 0.05$) (Table 5); on the other hand, no significant correlation between AFF_{AP} and the degree of vascular involvement was found ($P = 0.701$). The ROC curve analysis showed that

Table 3 Results of logistic regression analysis for AVN according to the severity of initial displacement

Index	AVN		*t*	*P*
	Yes	No		
T_{AP} (%)	30.3 ± 19.2	20.8 ± 18.6	2.313	0.023#
T_L (%)	40.9 ± 26.8	20.3 ± 25.0	3.684	< 0.001#
A_{AP} (°)	35.5 ± 18.3	18.8 ± 25.9	3.164	0.002#
A_L (°)	52.6 ± 27.7	22.0 ± 23.6	5.645	< 0.001#
AFF_{AP} (°)	56.2 ± 13.3	56.9 ± 13.8	0.251	0.802

T_{AP}, percentage of translation related to distal fracture line on AP view of radiographs

T_L, percentage of translation related to distal fracture line on lateral view of radiographs

A_{AP}, the angle between the fracture lines on AP view of radiographs

A_L, the angle between the fracture lines on lateral view of radiographs

AFF_{AP}, the angle between the distal fracture line and the femoral shaft axis on AP view of radiographs

AVN, avascular necrosis

S.E, standard error

RR, relative risk

CI, confidence interval

# $p < 0.05$

Table 4 Analysis of AVN according to the amount of T_{AP}, T_L, A_{AP}, A_L, and AFF_{AP}

	Coefficient	S.E.	Wald	*P*	RR	95% CI
T_{AP}	0.026	0.012	4.790	0.029#	1.026	1.003, 1.050
T_L	0.027	0.008	10.656	0.001#	1.028	1.011, 1.045
A_{AP}	0.025	0.009	8.353	0.004#	1.026	1.008, 1.044
A_L	0.041	0.009	19.996	< 0.001#	1.042	1.023, 1.061
AFF_{AP}	− 0.004	0.016	0.064	0.800	0.996	0.964, 1.028

T_{AP}, percentage of translation related to distal fracture line on AP view of radiographs

T_L, percentage of translation related to distal fracture line on lateral view of radiographs

A_{AP}, the angle between the fracture lines on AP view of radiographs

A_L, the angle between the fracture lines on lateral view of radiographs

AFF_{AP}, the angle between the distal fracture line and the femoral shaft axis on AP view of radiographs

AVN, avascular necrosis

# $p < 0.05$

T_{AP}% over 37.4% and T_L% over 29% were the cut-off values for increased incidence of AVN; similarly, A_{AP} over 8° and A_L over 18.6° were the cut-off values for an increased incidence of AVN. Chi-square tests also confirmed these findings (Table 6). Additionally, the ROC curve analysis indicated that the amount of initial translation is a better predictor of AVN than angulation is, as the mean diagnostic accuracy of T_{AP}% and T_L% (74%–75%) were significantly better than that of A_{AP} and A_L (65%–66%) (Table 7).

Table 5 Spearman's correlation analysis of initial displacement and degree of vascular involvement

Index	Value	AVN (*n*)		χ^2	*P*
		Yes	No		
T_{AP}	> 37.4%	12	16	1.484	0.002#
	≤ 37.4%	11	69		
T_L	> 29%	20	20	19.172	< 0.001#
	≤ 29%	8	60		
A_{AP}	> 8°	27	36	22.570	< 0.001#
	≤ 8°	1	44		
A_L	> 18.6°	25	33	19.249	< 0.001#
	≤ 18.6°	3	47		

T_{AP}, percentage of translation related to distal fracture line on AP view of radiographs

T_L, percentage of translation related to distal fracture line on lateral view of radiographs

A_{AP}, the angle between the fracture lines on AP view of radiographs

A_L, the angle between the fracture lines on lateral view of radiographs

AFF_{AP}, the angle between the distal fracture line and the femoral shaft axis on AP view of radiographs

# $p < 0.05$

Table 6 Analysis of AVN according to the amount of T_{AP}, T_L, A_{AP}, A_L, and AFF_{AP}

Initial displacement	Correlation coefficient	*P*
T_{AP} (%)	0.232	0.016#
T_L (%)	0.339	< 0.001#
A_{AP} (°)	0.388	< 0.001#
A_L (°)	0.453	< 0.001#
AFF_{AP} (°)	−0.037	0.701

T_{AP}, percentage of translation related to distal fracture line on AP view of radiographs

T_L, percentage of translation related to distal fracture line on lateral view of radiographs

A_{AP}, the angle between the fracture lines on AP view of radiographs

A_L, the angle between the fracture lines on lateral view of radiographs

AVN, avascular necrosis

# $p < 0.05$

The chi-square test did not find any significant difference in the incidence of AVN between the medial and lateral translation AP radiograph views ($\chi^2 = 2.039$, $P = 0.363$). However, posterior translation led to a significantly higher incidence of AVN than anterior translation did ($\chi^2 = 12.111$, $P = 0.002$) (Table 8).

In addition, chi-square tests showed that fractures with a comminuted medial cortex on AP radiographs (16 hips; 14.8%) were significantly associated with an increased rate of AVN compared with those without (92 hips; 85.2%) ($\chi^2 = 8.994$, $P = 0.005$; Table 9). On the other hand, the rate of AVN of fractures with a comminuted posterior cortex on lateral radiographs of (19 hips; 17.6%) was similar to those without (89 hips; 82.4%) ($\chi^2 = 3.143$, $P = 0.089$).

Table 7 Sensitivity, specificity, and diagnostic accuracy of T_{AP}, T_L, A_{AP}, and A_L to predict AVN

Direction of translation		AVN (*n*)		χ^2	*P*
		Yes	No		
AP radiographs	No translation	4	16	2.039	0.363
	Medial	7	11		
	Lateral	17	53		
Lateral radiographs	No translation	4	29	12.111	0.002#
	Anterior	7	31		
	Posterior	17	20		

Diagnostic accuracy = 100% × (true AVN + true non-AVN)/Total

T_{AP}, percentage of translation related to distal fracture line on AP view of radiographs

T_L, percentage of translation related to distal fracture line on lateral view of radiographs

A_{AP}, the angle between the fracture lines on AP view of radiographs

A_L, the angle between the fracture lines on lateral view of radiographs

Table 8 Analysis of AVN according to the direction of translation on AP and lateral pelvis radiographs

Direction of translation		AVN (*n*)		χ^2	*P*
		Yes	No		
AP radiographs	No translation	4	16	2.039	0.363
	Medial	7	11		
	Lateral	17	53		
Lateral radiographs	No translation	4	29	12.111	0.002#
	Anterior	7	31		
	Posterior	17	20		

AP, anteroposterior

AVN, avascular necrosis

# $p < 0.05$

Discussion

The current study indicates that the amount of initial displacement on plain radiographs is an important risk factor for AVN in children with femoral neck fracture, as previously reported [4, 7, 8] and that the incidence of AVN increased with the severity and the direction of the displacement. However, several studies have reported conflicting results [9, 10]. This controversy may be attributed to the disagreement among the multiple definitions of displacement and the relatively small sample sizes of previously published studies [9, 10].

Our analysis found that the incidence of AVN significantly increased with the severity of displacement. At present, most studies have evaluated the effect of displacement on the incidence of AVN by assessing fractures as "displaced" or "not displaced" [4, 7–10]. However, this method of assessing fracture displacement does not provide any information about the role of amount (severity) or direction of displacement (translation and angulation) in the onset of AVN.

In the present study, both the amount (in degrees) and direction (translation and angulation) of the displacement were evaluated on the AP and lateral radiographs. Interestingly, we found that the severity of displacement correlates with an increased rate of AVN and an increased

Table 9 Analysis of AVN secondary to comminuted fracture of the medial cortex (AP radiographs) and of the posterior cortex (lateral radiographs)

		AVN(*n*)		χ^2	*P*
		Yes	No		
Medial cortex	Comminuted	9	7	8.994	0.005#
	Without comminution	19	73		
Posterior cortex	Comminuted	8	11	3.143	0.089
	Without comminution	20	69		

# $p < 0.05$

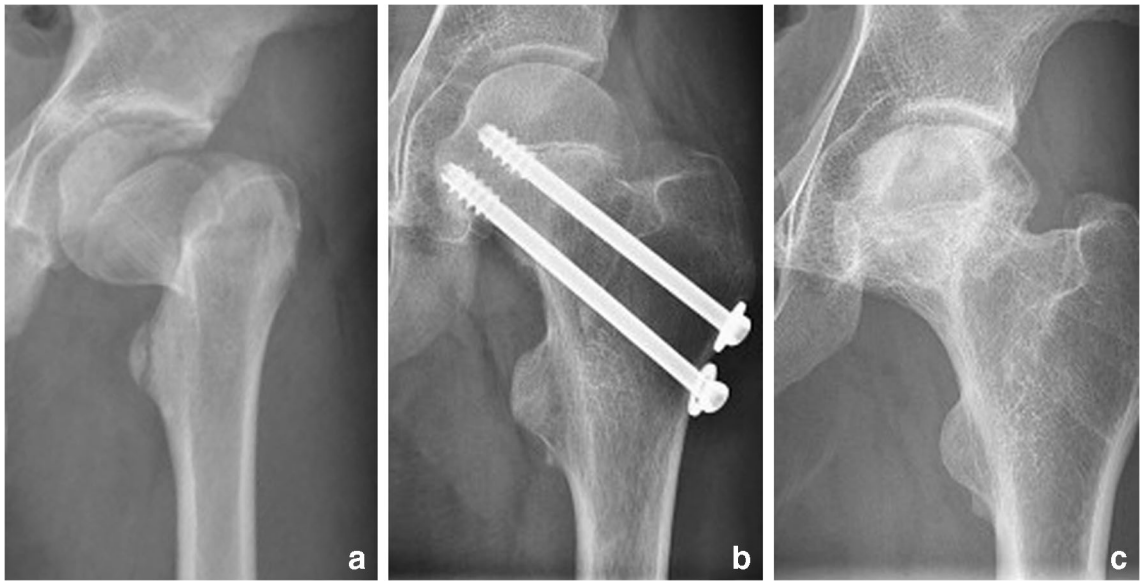

Fig. 3 Radiographs of a 10-year-old girl with a displaced femoral neck fracture. **a** Anteroposterior (AP) view of a Delbet-Colonna type-II fracture, with the amount of initial translation (T_{AP}) over 37.4%. **b** AP view after closed reduction and cannulated screw fixation within 24 h from injury. **c** 18 months after surgical treatment showing AVN of the femoral head

degree of vascular involvement in children with femoral neck fracture. Previous studies have shown that the AVN rate is higher in fractures that are secondary to high-energy trauma and those with a greater amount of initial displacement. This result is probably related to damage of vessels supplying the femoral head at the time of injury [6–17]. Interestingly, we found the amount of initial translation increased with the type of fracture although patients with type III and type II fractures had similar AVN rate ($P = 0.528$). Our results are in accordance with previous studies, which reported that type of fracture cannot be considered a major risk factor for AVN [9, 18]. Additionally, we found that patients with more severe initial fracture displacement had poorer quality of reduction than those with milder displacement (Table 2). Several studies have reported that poor quality of reduction could significantly increase the incidence of AVN [5, 7, 19].

Our study also found that T_{AP}% over 37.4% and T_L% over 29% were the cut-off values for increased incidence of AVN (Figs. 3 and 4); similarly, A_{AP} over 8° and A_L over 18.6° were the cut-off values for increased incidence of AVN (Figs. 5 and 6). ROC analysis found that the quality

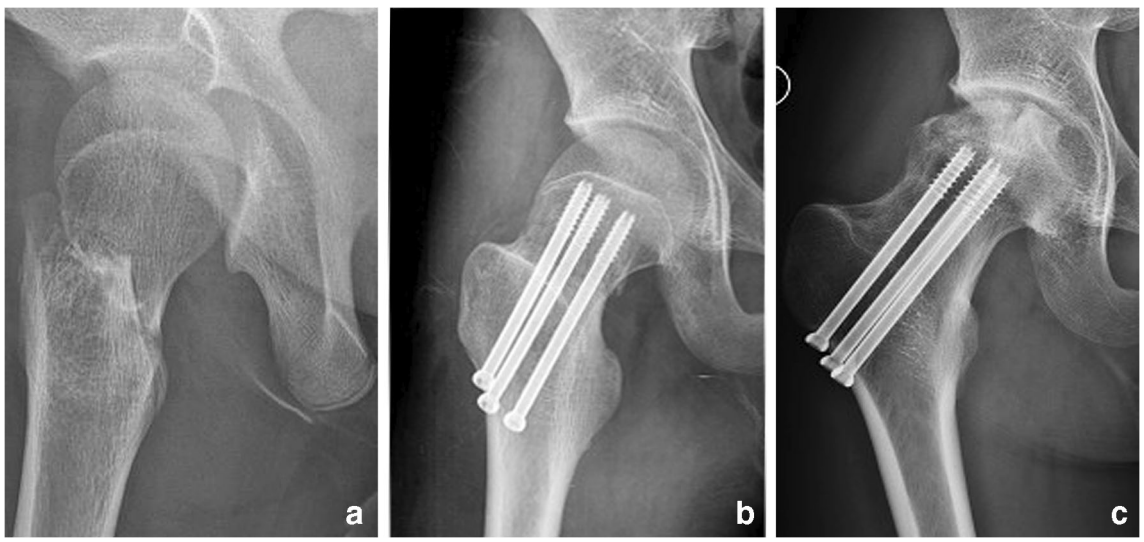

Fig. 4 Radiographs of a 12-year-old boy with a displaced femoral neck fracture. **a** Lateral (L) view of a Delbet-Colonna type-II fracture, with the amount of initial translation (T_L) over 29%. **b** AP view after closed reduction and cannulated screw fixation within 24 h from injury. **c** 24 months after surgical treatment showing AVN of the femoral head

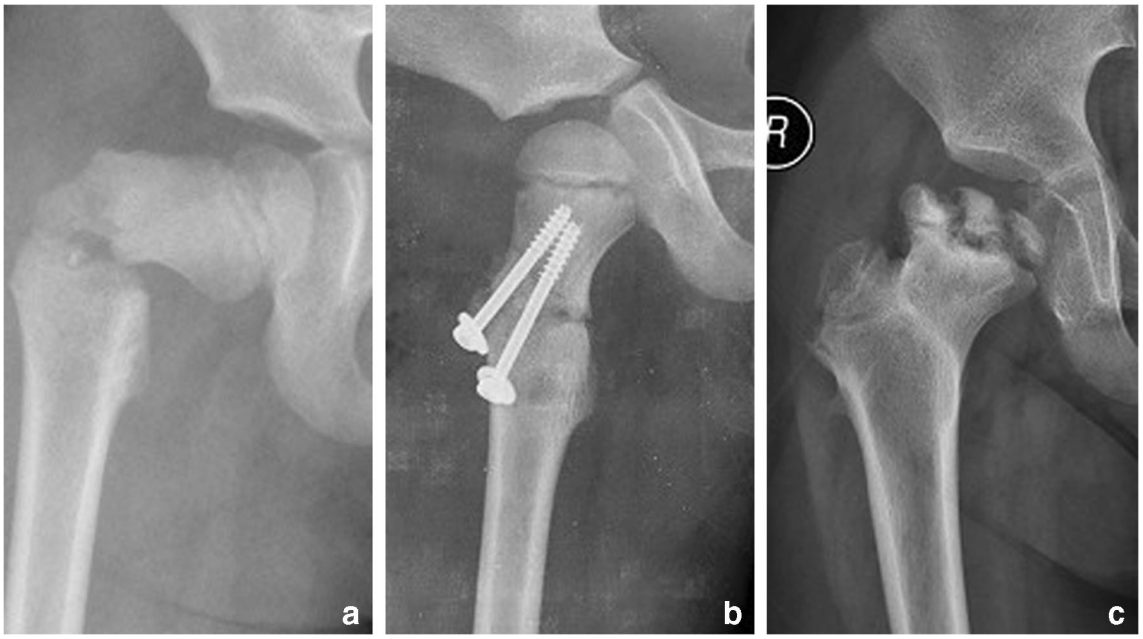

Fig. 5 Radiographs of a 7-year-old boy with a displaced femoral neck fracture. **a** Anteroposterior (AP) view of a Delbet-Colonna type-III fracture, with the amount of initial angulation (A_{AP}) over 8°. **b** AP view after closed reduction and cannulated screw fixation within 48 h from injury. **c** 26 months after surgical treatment showing AVN of the femoral head

of reduction negatively correlated with T_{AP}%, T_L%, A_{AP}, and A_L ($P < 0.05$) (Table 2), while no significant correlation between AFF_{AP} and the type of fracture was found ($P = 0.722$). Overall, the mean diagnostic accuracy of the amount of translation (T_{AP}% and T_L%) was significantly better than that of the amount of angulation (A_{AP} and A_L). In our opinion, this finding may be more attributed to the higher chances of direct injury and/or kinking of the vessels supplying the femoral head during translation than to angulation.

None of the previously published studies have investigated the effects of the direction of displacement on the incidence of AVN in children with femoral neck fractures. Our study found that posterior translation was significantly associated with an

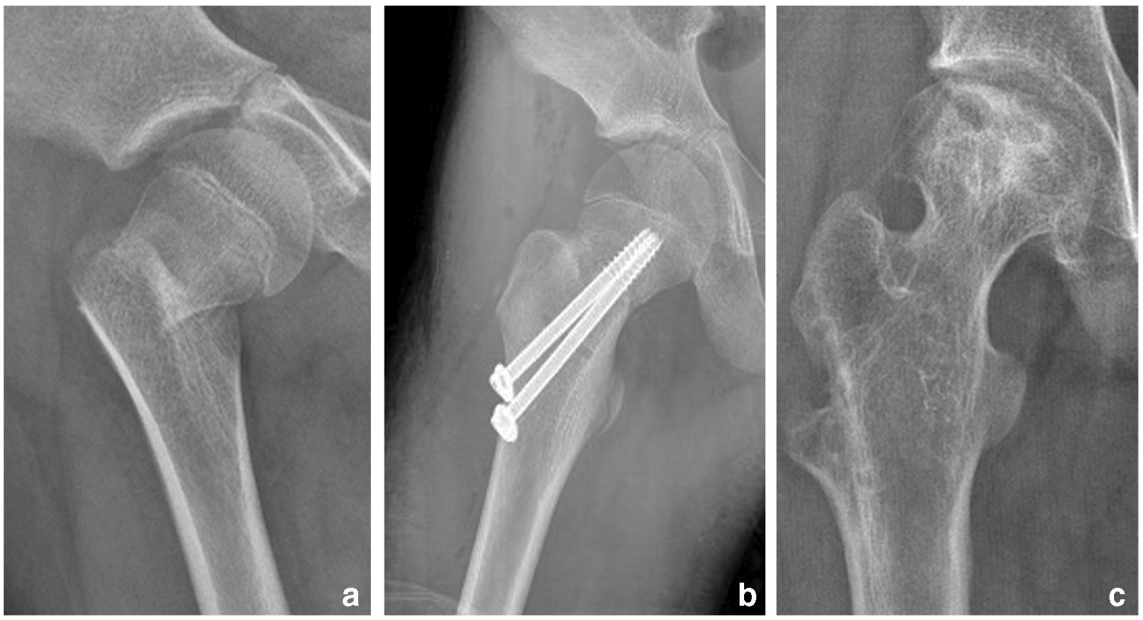

Fig. 6 Radiographs of an 11-year-old girl with a displaced femoral neck fracture. **a** Lateral (L) view of a Delbet-Colonna type-II fracture, with the amount of initial angulation (A_L) over 18.6°. **b** AP view after open reduction and cannulated screw fixation within 24 h from injury. **c** 28 months after surgical treatment showing AVN of the femoral head

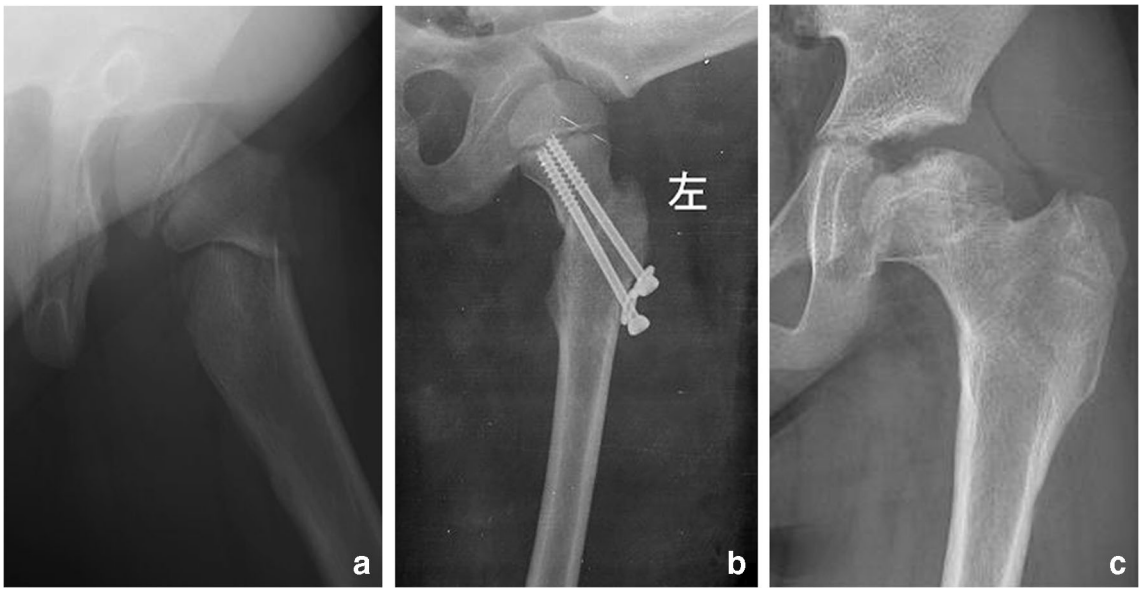

Fig. 7 Radiographs of an 8-year-old boy with a displaced femoral neck fracture. **a** Lateral (L) view of a Delbet-Colonna type-II fracture with a posterior translation. **b** AP view after closed reduction and cannulated screw fixation within 72 h from injury. **c** 26 months after surgical treatment showing AVN of the femoral head

increased risk of AVN compared with anterior translation (Fig. 7). In our opinion, when posterior translation occurs, it may damage the deep branch of the medial femoral circumflex artery (MFCA). Several studies have shown that the terminal branch of the MFCA, the posterior–superior nutrient artery, is the most important artery providing the blood supply to the femoral head [20–22].

Interestingly, we also found that fractures with a comminuted medial cortex on AP radiographs were significantly associated with an increased rate of AVN compared with those without (Fig. 8, Table 9). In our opinion, the higher rate of AVN can also be explained by a higher chance of damage to the MFCA because medial comminution is usually secondary to higher energy trauma that ultimately tends to displace the medial column, where the MFCA runs, thus making it more vulnerable to injury [20–22]. Additionally, the mechanical instability of fractures with medial comminution may also contribute to the increased AVN rate

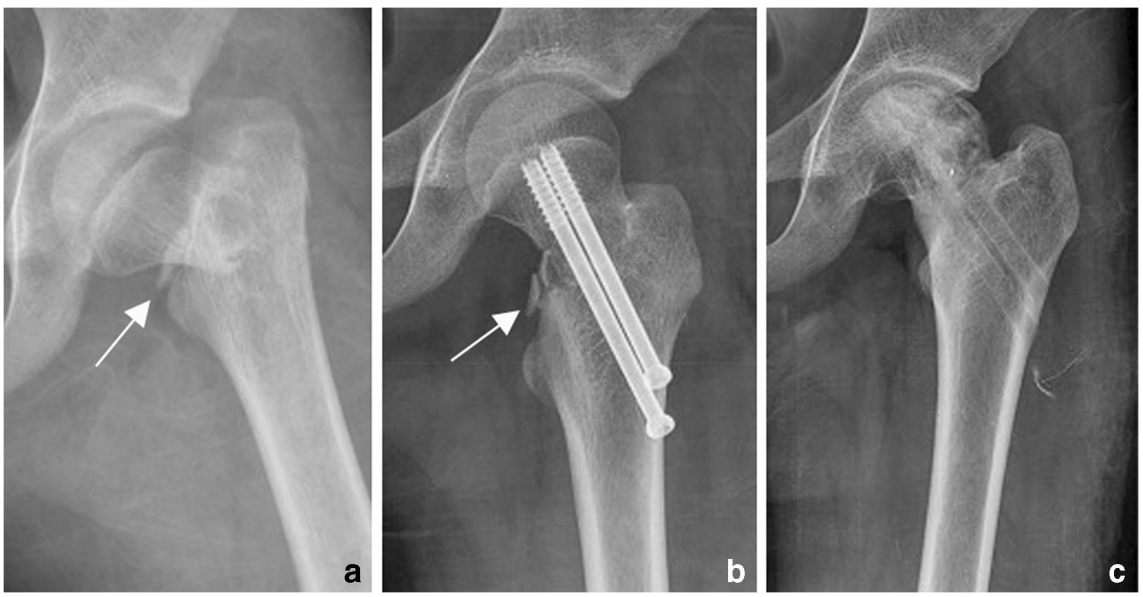

Fig. 8 Radiographs of a 13-year-old girl with a displaced femoral neck fracture. **a** Anteroposterior (AP) view of a Delbet-Colonna type-III fracture with a comminuted medial cortex. **b** AP view after closed reduction and cannulated screw fixation within 48 h from injury. **c** 17 months after surgical treatment showing AVN of the femoral head

[23–27]. In particular, Ripamonti et al. and Macahdo et al. reported that a lack of medial cortical support increases the risk of varus displacement [28, 29]. Moreover, through a finite element model, Machado et al. found that the stress on the femoral head significantly increases in models with coxa vara deformity [29]. Several studies reported no association between the time of treatment or method of reduction of femoral neck fractures in children and the risk of osteonecrosis of the femoral head; only 11/108 fractures were treated more than 7 days from initial trauma and 90.2% were treated within 96 h [8, 30, 31].

It should be noted that there are still some limitations in the present study. First, this is a retrospective study. Second, the amount of rotation of the distal fragment could not be considered because all measurements were performed only on plain radiographs (AP and lateral view). Therefore, it is possible that our measurements do not fully reflect the true amount of initial displacement. However, all radiographs were consistently assessed, and two experienced pediatric orthopedic surgeons performed all the measurements. Thirdly, several patients (86.1%) could not be treated within the first 24 h from injury because most of them came from remote locations and requires time to reach the referring institution (sometimes more than one day of traveling). However, no significant correlation between the rate of AVN and the time to reduction and surgical fixation was found. Our results agreed with previous studies, reporting time of fracture fixation cannot be considered as a risk factor for AVN [8–10].

In conclusion, the incidence of AVN in children with femoral neck fractures increases with the severity of initial displacement. Translation over 37.4% and 29% on AP (T_{AP}%) and lateral (T_L%) radiographs and angulation over 8° and 18.6° on AP (A_{AP}) and lateral (A_L) radiographs, respectively, are associated with an increased risk of AVN in children with femoral neck fractures. The amount of initial translation is a better predictor of AVN than angulation and fracture with posterior translation and/or medial comminution has a significantly higher incidence of AVN.

Acknowledgments We thank Yuancheng Pan, Xiaokun Lu, Guoxin Nan, Chongzhi Zhao, and Yaoxi Liu for the data collection.

Compliance with ethical standards

The authors declare that they have no conflict of interest. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

All procedures were performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

This is a retrospective study, and an IRB approval was obtained (approval no. 20190301).

References

1. Davison BL, Weinstein SL (1992) Hip fractures in children: a long-term follow-up study. J Pediatr Orthop 12:355–358
2. Mirdad T (2002) Fractures of the neck of femur in children: an experience at the Aseer Central Hospital, Abha, Saudi Arabia. Injury 33:823–827
3. Bimmel R, Bakker A, Bosma B, Michielsen J (2010) Paediatric hip fractures: a systematic review of incidence, treatment options and complications. Acta Orthop Belg 76:7–13
4. Spence D, Di Mauro JP, Miller PE, Glotzbecker MP, Hedequist DJ, Shore BJ (2016) Osteonecrosis after femoral neck fractures in children and adolescents: analysis of risk factors. J Pediatr Orthop 36:111–116. https://doi.org/10.1097/BPO.0000000000000424
5. Shrader MW, Jacofsky DJ, Stans AA, Shaughnessy WJ, Haidukewych GJ (2007) Femoral neck fractures in pediatric patients: 30 years experience at a level 1 trauma center. Clin Orthop Relat Res 454:169–173. https://doi.org/10.1097/01.blo.0000238794.82466.3d
6. Dendane MA, Amrani A, El Alami ZF, El Medhi T, Gourinda H (2010) Displaced femoral neck fractures in children: are complications predictable? Orthop Traumatol Surg Res 96:161–165. https://doi.org/10.1016/j.rcot.2010.02.004
7. Morsy HA (2001) Complications of fracture of the neck of the femur in children. A long-term follow-up study. Injury 32:45–51
8. AlKhatib N, Younis MH, Hegazy A, Ibrahim T (2019) Early versus late treatment of paediatric femoral neck fractures: a systematic review and meta-analysis. Int Orthop 43:677–685. https://doi.org/10.1007/s00264-018-3998-4
9. Riley PM Jr, Morscher MA, Gothard MD, Riley PM Sr (2015) Earlier time to reduction did not reduce rates of femoral head osteonecrosis in pediatric hip fractures. J Orthop Trauma 29:231–238. https://doi.org/10.1097/BOT.0000000000000226
10. Inan U, Köse N, Omeroğlu H (2009) Pediatric femur neck fractures: a retrospective analysis of 39 hips. J Child Orthop 3:259–264. https://doi.org/10.1007/s11832-009-0180-y
11. Clohisy JC, Carlisle JC, Beaulé PE, Kim YJ, Trousdale RT, Sierra RJ, Leunig M, Schoenecker PL, Millis MB (2008) A systematic approach to the plain radiographic evaluation of the young adult hip. J Bone Joint Surg Am 90(Suppl 4):47–66. https://doi.org/10.2106/JBJS.H.00756
12. Siebenrock KA, Kalbermatten DF, Ganz R (2003) Effect of pelvic tilt on acetabular retroversion: a study of pelves from cadavers. Clin Orthop Relat Res 407:241–248. https://doi.org/10.1097/00003086-200302000-00033
13. Colonna PC (1929) Fracture of the neck of the femur in children. Am J Surg 6:793
14. Song KS (2010) Displaced fracture of the femoral neck in children: open versus closed reduction. J Bone Joint Surg (Br) 92:1148–1151. https://doi.org/10.1302/0301-620X.92B8.24482
15. Ratliff AH (1962) Fractures of the neck of the femur in children. J Bone Joint Surg (Br) 44:528–542
16. Quick TJ, Eastwood DM (2005) Pediatric fractures and dislocations of the hip and pelvis. Clin Orthop Relat Res 432:87–96. https://doi.org/10.1097/01.blo.0000155372.65446.40
17. Swiontkowski MF, Winquist RA (1986) Displaced hip fractures in children and adolescents. J Trauma 26:384–388
18. Varshney MK, Kumar A, Khan SA, Rastogi S (2009) Functional and radiological outcome after delayed fixation of femoral neck fractures in pediatric patients. J Orthop Traumatol 10:211–216. https://doi.org/10.1007/s10195-009-0072
19. Stone JD, Hill MK, Pan Z, Novais EN (2015) Open reduction of pediatric femoral neck fractures reduces osteonecrosis risk. Orthopedics 38:e983–e990. https://doi.org/10.3928/01477447-20151020-06

20. Zlotorowicz M, Czubak J, Caban A, Kozinski P, Boguslawska-Walecka R (2013) The blood supply to the femoral head after posterior fracture/dislocation of the hip, assessed by CT angiography. Bone Joint J 95-B:1453–1457. https://doi.org/10.1302/0301-620X.95B11.32383
21. Zlotorowicz M, Szczodry M, Czubak J, Ciszek B (2011) Anatomy of the medial femoral circumflex artery with respect to the vascularity of the femoral head. J Bone Joint Surg (Br) 93:1471–1474. https://doi.org/10.1302/0301-620X.93B11.26993
22. Lavigne M, Kalhor M, Beck M, Ganz R, Leunig M (2005) Distribution of vascular foramina around the femoral head and neck junction: relevance for conservative intracapsular procedures of the hip. Orthop Clin North Am 36:171–176. https://doi.org/10.1016/j.ocl.2005.02.002
23. Xiong WF, Chang SM, Zhang YQ, Hu SJ, Du SC (2019) Inferior calcar buttress reduction pattern for displaced femoral neck fractures in young adults: a preliminary report and an effective alternative. J Orthop Surg Res 14:70. https://doi.org/10.1186/s13018-019-1109-x
24. Ye Y, Chen K, Tian K, Li W, Mauffrey C, Hak DJ (2017) Medial buttress plate augmentation of cannulated screw fixation in vertically unstable femoral neck fractures: surgical technique and preliminary results. Injury 48:2189–2193. https://doi.org/10.1016/j.injury.2017.08.017
25. Zhang YQ, Chang SM (2013) Mechanism of "Gotfried reduction" in femoral neck fracture. J Orthop Trauma 27:e291. https://doi.org/10.1097/BOT.0000000000000007
26. Kalra M, Anand S (2001) Valgus intertrochanteric osteotomy for neglected femoral neck fractures in young adults. Int Orthop 25:363–366. https://doi.org/10.1007/s002640100288
27. Said GZ, Farouk O, Said HG (2010) Valgus intertrochanteric osteotomy with single-angled 130° plate fixation for fractures and non-unions of the femoral neck. Int Orthop 34:1291–1295. https://doi.org/10.1007/s00264-009-0885-z
28. Ripamonti C, Lisi L, Avella M (2014) Femoral neck shaft angle width is associated with hip-fracture risk in males but not independently of femoral neck bone density. Br J Radiol 87:20130358. https://doi.org/10.1259/bjr.20130358
29. Machado MM, Fernandes PR, Zymbal V, Baptista F (2014) Human proximal femur bone adaptation to variations in hip geometry. Bone 67:193–199. https://doi.org/10.1016/j.bone.2014.07.001
30. Panigrahi R, Sahu B, Mahapatra AK, Palo N, Priyadarshi A, Biswal MR (2015) Treatment analysis of paediatric femoral neck fractures: a prospective multicenter theraupetic study in Indian scenario. Int Orthop 39(6):1121–1127. https://doi.org/10.1007/s00264-015-2677-y
31. Zielinski SM, Meeuwis MA, Heetveld MJ, Verhofstad MH, Roukema GR, Patka P, Van Lieshout EM (2013) Adherence to a femoral neck fracture treatment guideline. Int Orthop 37(7):1327–1334. https://doi.org/10.1007/s00264-013-1888-3