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Long-term outcome of robotic-guided closed reduction internal fixation for Delbet II femoral neck fractures in children

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Abstract

Objective To retrospectively analyze and assess the long-term effectiveness of robotic navigation and traditional closed reduction internal fixation in the treatment of Delbet type II femoral neck fracture in children.

Methods A total of fifty-five patients diagnosed with pediatric Delbet type II femoral neck fracture, who were admitted to Foshan Hospital of Traditional Chinese Medicine between January 2018 and June 2022, were included in this study. Among them, 22 cases of nailing under robotic navigation were set as the observation group, and 33 cases of nailing under fluoroscopy of the C-arm machine were set as the control group. All patients had their femoral neck fractures closed and repositioned first. After confirming the satisfactory fracture repositioning under the fluoroscopic view of the C-arm machine, internal fixation was performed by inserting hollow compression screws in the corresponding surgical way.A comparative analysis was conducted between the two groups to assess the disparity in the amount of X-ray exposure during surgery, the number of guide pins inserted, and the duration of the surgical procedure. The quality of comparative fracture reduction was assessed according to the Haidukewych criteria on the first postoperative hip X-ray, and the parallelism and distribution of the comparative screws were measured. The incidence of hip function and postoperative complications according to the Ratliff criteria were evaluated between each of the subgroups at the final follow-up.

Results Comparison of general information, operation duration, and quality of fracture reduction between the two groups failed to reveal statistically significant results ($P > 0.05$). The observation group had a lower number of X-ray exposures and guide pin placements compared to the control group, and this difference was statistically significant ($P < 0.05$).At the last follow-up, the observation group exhibited superior screw parallelism and distribution, as well as hip joint function, compared to the control group, and this difference was statistically significant ($P < 0.05$). The incidence of complications in the observation group was lower than that in the control group; however, the difference was not statistically significant ($P > 0.05$).

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Conclusion Closed reduction and internal fixation under orthopedic robot navigation can achieve better long-term efficacy in treating Delbet type II femoral neck fracture in children.

Keywords TiRobot orthopaedic robot, Navigated nail placement, Delbet type II pediatric femoral neck fracture, Closed reduction internal fixation

Introduction

Proximal femur fracture in children is an uncommon fracture that occurs as a result of a high-energy accident, making up less than 1% of all fractures in children [1]. There is no clear consensus on the optimal treatment of such fractures. Moreover, the lack of stratification of outcomes prevents orthopedic surgeons from taking the most appropriate treatment according to patient's age [2]. Delbet type II fracture (trans-trochanteric femoral neck fracture) is the predominant type of proximal femur fracture in children, constituting around 47% of hip fractures in children [3]. There are many current reports of orthopedic robotic navigation for the treatment of adult femoral neck fractures; however, there are very few reports of its application for the treatment of pediatric femoral neck fractures, especially the long-term clinical outcomes. This study conducted a systematic evaluation to assess the long-term effectiveness of two surgical styles of nailing under closed-displacement robotic navigation and freehand nailing under fluoroscopy of conventional C-arm machines in Delbet type II femoral neck fractures in children in our hospital from January 2018 to June 2022 and was reported as follows.

Materials and methods

Study design and patients

We chose patients with unilateral Delbet type II pediatric closed reduction internal fixation of femoral neck fracture aged 4–16 years who were hospitalized in Foshan Hospital of Traditional Chinese Medicine from January 2018 to June 2022. All patients were diagnosed by X-ray film and CT before operation, and we excluded patients who underwent incision and reduction surgery and those who combined with serious basic diseases. Robot-guided subnailing was set as the observation group, and traditional C-arm fluoroscopic machine-assisted subnailing was set as the control group. Prior to the surgical procedure, all individuals involved provided their signature on an informed consent document.

Surgical technique

Following a successful administration of anesthetic, the injured limb was positioned on the orthopedic traction bed for axial traction of the lower limb.Subsequently, the limb was gently manipulated by performing abduction and internal rotation in order to realign the fracture, avoiding repeated operations. A C-arm fluoroscopy was conducted to verify the successful realignment of the fracture, and then we cleansed the skin and draped the area. In the observation group, nailing was performed under the navigation of TiRobot (Beijing Tianzhihang Medical Technology Co., Ltd.), the tracer was positioned on the anterior superior iliac spine of the afflicted side, the ruler was adjusted, and the C-arm was linked to capture frontal and lateral images of the femoral head and neck that covered at least 10 robotic localization marking points; the paths and lengths of three hollow and compression screws were virtually planned parallel to the femoral neck in an inverted zigzag distribution. The paths and lengths of the three hollow compression screws were virtually planned on the images (in order to maintain the stability of the fractured end and prevent it from penetrating the femoral epiphysis); then the robot arm moved according to the planned paths and approached the skin under the monitoring of the robot's master control system, and an incision measuring 1 centimeter in length was created in the skin at the location where each prepositioned screw was placed. Then the guide sleeve was inserted along the incision and fixed to the femur, and the guide pins were drilled into the skin to place the hollow compression screws of the appropriate lengths, respectively, and the robotic planning for the nailing is shown in Figs. 1 and 2. In the control group, under C-arm fluoroscopy, the operator used the lower part of the greater trochanter as the entry point according to his experience, and inserted 3 guide pins along the femoral neck in an inverted zig-zag manner with his bare hands, avoiding passing through the epiphysis as much as possible, and then adjusted the guide pins to the position and depth of the fracture after the position and depth of the guide pins were satisfied with C-arm fluoroscopy, and then used the appropriate hollow screws for pressure fixation of the fracture end. Ultimately, after the adequacy of the screw's position and length was determined to be satisfactory by C-arm fluoroscopy, the guide pins were withdrawn, the operative area was irrigated, and the operative opening was closed.

Postoperative treatment and follow-up

After surgery, both groups were immobilized with a hip herringbone cast or brace for 6–8 weeks. In the first half year after surgery, the individuals were followed upon a monthly basis, after half a year at least once every three months, and after one year at least once every six months. At the time of follow-up, the positive and lateral X-ray images of the hip joint should be reviewed.

Fig. 1 Robot planning nail placement paths

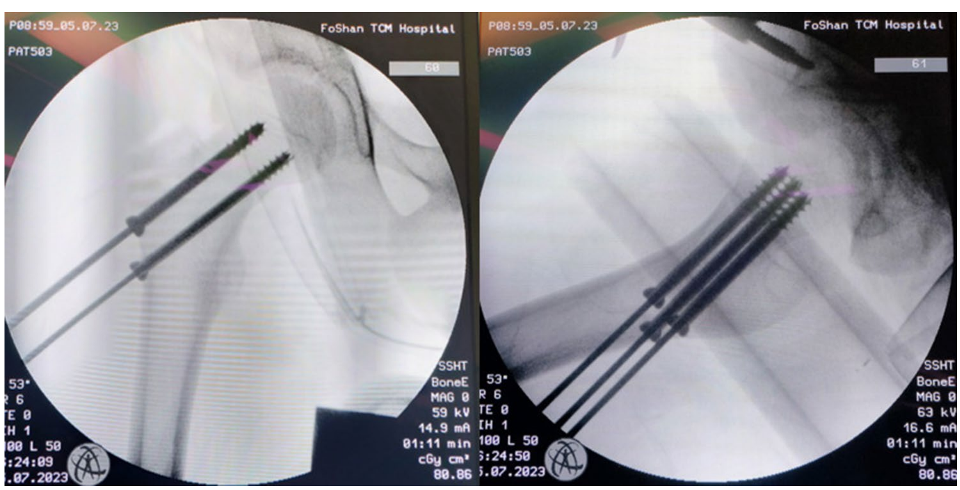

Fig. 2 Completion of nail placement according to the planned path

Imagery and functional evaluation

After the surgery, the researchers conducted a comparison between the quantity of X-ray exposures throughout the operation, the quantity of guide pin placements, and the time of the procedure between the two groups. The first postoperative orthopantomographs of the hip joint were evaluated and compared with the quality of fracture alignment based on the Haidukewych criteria [4]: excellent: displacement less than 2 mm, angulation less than 5 degrees; good: displacement between 2 and 5 mm, angulation between 5 and 10 degrees; acceptable: displacement between 5 and 10 mm, angulation between 10 and 20 degrees; poor: displacement greater than 10 mm, angulation greater than 20 degrees. The parallelism and distribution of the contrasting hollow compression screws were measured by measuring the angle between the axis of the femoral shaft and the longitudinal axis of each screw on the orthopantomographs, and the average of the difference in the angle between the two screws was the parallelism [5, 6, 7]; on the orthopantomographs, the distance between the farthest boundaries of the screws at the level of the fracture line/the width of the femoral neck×100% was the distribution.

According to the Ratliff criteria [7], the hip function of both groups was contrasted at the final follow-up: excellent: no pain in the affected hip, normal hip joint and daily activities, and normal morphology of the femoral neck on imaging; good: intermittent pain in the affected hip, with a restriction of hip joint movements by less than 50%, can carry out their typical daily activities, and slight

Table 1 Comparison of general information between the two groups

	Observation group	Control group	P value
	Median(IQR)	Median(IQR)	
Age	13(13 to 14)	13(10 to 14)	0.663*
Time from injury to surgery (hour)	98.5(72 to 140)	104(63 to 143)	0.897*
Follow-up period (month)	33(28 to 42)	35(29 to 40)	0.884*
Gender	n.(%)	n.(%)	
Male	15(68.2%)	24(72.7%)	0.716**
Female	7(31.8%)	9(27.3%)	
Injured side			
Left	8(36.4%)	16(48.5%)	0.375**
Right	14(63.6%)	17(51.5%)	
Causes of injury			
Fall	11(50.0%)	21(63.7%)	0.188**
Traffic accidents	6(27.3%)	3(9.1%)	
Exercise	1(4.5%)	5(15.2%)	
Slip	4(18.2%)	4(12.0%)	

IQR; Interquartile range, *Mann-Whitney U Test, **Chi-Square - Fisher's Exact Tests

shortening deformity of the femoral neck on imaging; and poor: severe pain in the hip, limitation of hip joint activity>50%, limitation of daily activity; imaging suggests serious shortening deformity of the femoral neck and degenerative joint changes.

During the follow-up period, we compared the occurrence of complications, including ischemic necrosis of the femoral head (Avascular Necrosis, AVN), femoral neck nonunion, premature epiphyseal closure, and internal rotation of the hip, between each of the groups.

Statistical analysis

The statistical analysis was performed with SPSS 26.0. Count data: the x^2 test was employed for comparing categorical data between different groups, whereas the Mann-Whitney U test was used for comparing hierarchical data between different groups (one-way ordered categorical variables). Measurement data: the S-W normal distribution test was performed first, and data that followed the normal distribution was presented as mean±standard deviation ($\bar{x} \pm s$), and data that deviated from the normal distribution were represented using the median and interquartile range (Md, P25-P75). The t-test was employed to compare data between different groups that followed a normal distribution and had equal variances(the t′-test was used for a lack of uniformity in the variance), and the rank-sum test was used for non-normally distributed data. The test had a significance level of $\alpha = 0.05$.

Table 2 Comparison of surgical operation indexes between the two groups

	Observation Group	Control group	P value
Number of exposures (times)	6.09 ± 1.69	10.42 ± 2.19	< 0.001*
Number of needle insertions (times)	3(3–4)	11(9–13)	< 0.001**
Duration of surgery (min)	80.27 ± 23.86	66.76 ± 26.80	0.061*

*T-Test, **Mann-Whitney U Test

Table 3 Comparison of imaging measurements between the two groups

	Observation Group	Control group	P value
Reset quality			
Excellent	11(50.0%)	13(39.4%)	0.264*
Good	7(31.8%)	13(39.4%)	
Acceptable	4(18.2%)	7(21.2%)	
Degree of parallelism (°)			
Orthopantomogram	1.15(0.81–1.83)	1.86(1.20–3.41)	0.036**
Lateral radiographs	0.82(0.57–0.99)	1.48(0.63–2.94)	0.013**
Distribution degree (%)			
Orthopantomogram	73.82 ± 9.82	60.03 ± 9.67	<0.001***
Lateral radiographs	63.58 ± 15.34	53.13 ± 17.61	0.028***

*Chi-Square - Fisher's Exact Tests, **Mann-Whitney U test, ***T-Test

Results

Comparison of grouping results and general information

Table 1 displays the inclusion of a total of 55 individuals, with 22 in the observation group and 33 within the control group. No statistically significant disparity was found between the two groups with regard to gender, age, time from accident to operation, injured side, cause of injury, and follow-up time ($P > 0.05$).

Comparison of surgical operation indexes

Table 2 demonstrates that the observation group exhibited a decreased frequency of intraoperative X-ray exposures and guide needle placements compared to the control group. This difference was statistically significant ($P < 0.05$). When comparing the length of surgery between the two groups, it was found that the observation group had a longer time in comparison with the control group. However, this difference was not considered statistically significant ($P > 0.05$).

Comparison of imaging measurement results

According to the data presented in Table 3, there was no statistically significant disparity in the quality of postoperative fracture reduction between the two categories ($P > 0.05$). The observation group has superior screw parallelism and distribution in comparison to the control group, with a statistically significant disparity ($P < 0.05$).

Comparison of hip function and complications

Table 4 demonstrates that the observation group exhibited a superior excellent rate (90.91%, 20/22) in comparison to the control group (78.79%, 26/33) at the last follow-up based on the Ratliff criterion. This difference was statistically significant ($P<0.05$). In the observation group, there were 7 cases with different degrees of AVN, of which 2 cases had necrosis severely involving the epiphysis secondary to limb shortening, and 1 case was combined with femoral neck nonunion; in the control group, there were 16 cases with different degrees of AVN, of which 4 cases had necrosis severely involving the epiphysis secondary to limb shortening, 2 cases were combined with femoral neck nonunion, and 1 case had hip endosteum. The occurrence of complications in the observation group (31.82%, 7/22) was reduced compared to the control group (48.48%, 16/33), but this difference was not statistically significant ($P>0.05$).

Discussion

Due to the special characteristics of the development of the proximal femoral epiphyseal plate in children, the arterial blood flow to the femoral head is different at different ages, and in the age group of 3–4 years to 14–16 years, femoral neck fractures in children, especially displaced fractures, have a higher likelihood of developing complications such as AVN and osteochondromas than in adults, which seriously affects the prognosis of the children [8]. Complications can be minimized if the principles of early intervention, joint decompression, and anatomical reduction are followed, which can be minimized [9]. Hollow compression screws are the accepted method for surgically treating femoral neck fractures in patients of all ages. Performing good screw placement in youngsters is challenging due to the tiny diameter of the femoral neck in contrast to adults, and the traditional approach requires experienced orthopedic surgeons to perform the procedure empirically under fluoroscopy of a C-arm machine, even repeatedly adjusting the direction of insertion of the guide pins, which may decrease the stability of the proximal femur [10]. Meanwhile, repetitive exposure to X-ray radiation amplifies the occurrence of radiological harm to both patients and medical staff [11]. In order to improve the accuracy of hollow screw placement, prevent complications, and reduce radiological medical injuries, in recent years, because to advancements of orthopedic robots recently, the utilization of robot-assisted internal fixation insertion technology has become increasingly prevalent in surgical procedures for adult femoral neck fractures [12–14], which has been proven to be a more effective way of placing nails, and compared with the traditional bare-handed placement of nails, it has the ability to significantly decrease the amount of X-ray exposures during surgery and lessen the duration of the operation [15], and the postoperative screw parallelism and distribution are also better. Compared with traditional freehand nailing, it can significantly decrease the amount of X-ray exposure during surgery and lessen the duration of the operation [12], and the parallelism and distribution of the screws are better after the operation. Recently, there has been a growing trend in using robots to assist in the nailing method for treating femoral neck fractures in children [10], but there are still few reports on its long-term efficacy.

The optimal timing for surgical intervention in pediatric patients with fractures in the femoral neck is currently a subject of intense controversy, with most scholars believing that early 24-hour fixation should be performed. It has also been argued that in developing nations, where patients typically encounter problems such as delayed referrals and a lack of awareness, it is difficult to perform early fixation surgery within 24 h. However, early fixing within 24–72 h after the injury is critical in preventing complications [16]. Factors such as the extent of the original displacement, the presence or absence of comminution of the medial or posterior cortex, and the quality of the reduction have a role in the healing of fractures in children. These factors affect both the time it takes for the fracture to heal and the likelihood of nonunion occurring; and the probability of fracture healing progressively increases in a linear manner within the initial 6 months of the fracture healing period, and then levels off with an increase of less than 5% per month [17]. It has been noted that the incidence of complications (femoral head necrosis, premature epiphyseal closure, and acetabular dysplasia) is significantly higher in children with Delbet II femoral neck fractures in the presence of free fracture fragments than in those without free fracture fragments [18]. The occurrence of AVN in pediatric patients with femur neck fractures can be attributed to several factors, including age, fracture classification, level of displacement, operative time, and extent of reduction. However, there is a notable correlation between the degree of initial displacement and the likelihood of AVN [1, 19, 20].

Table 4 Comparison of hip function rating and complications between the two groups

	Observation Group	Control group	*P* value
Hip joint function			
Excellent	15(68.2%)	11(33.3%)	0.016*
Good	5(22.7%)	15(45.5%)	
Poor	2(9.1%)	7(21.2%)	
Complications			
Yes	7(31.8%)	16(48.5%)	0.054*
No	15(68.2%)	17(51.5%)	

*Chi-Square - Fisher's Exact Tests

Meta-analysis revealed that the overall occurrence of AVN following proximal femoral fracture in pediatric patients is about 22%, and age and fracture type are important factors affecting AVN [21]. The results of a multicenter study involving 239 pediatric femoral neck fractures showed a higher incidence of AVN in older children (12 years of age) and suggested that this phenomenon was mainly related to the intraosseous trophic vascular injury directly caused during femoral neck fractures in older children [22]. In pediatric femoral neck fractures, the mechanism of injury and fracture characteristics are age-related. Early reduction should be performed as early as possible according to the safety of the child, but trans-epiphyseal fixation should be avoided in younger children.AVN may be caused by the characteristics of the injury (Delbet typing) rather than by the choice of treatment modality [23]. However, a different point of view has been proposed by a study of Delbet type 2 fractures, which showed that factors pertaining to the treatment process, apart from the seriousness of the injury and the initial misalignment of the broken bone, did not have a notable impact on the occurrence of AVN, and it was concluded that age did not pose a risk for the development of AVN in those individuals [24].

On the other hand, whether the closed or open reduction of the fracture is a risk cause for AVN is currently controversial. For example, several scholars have conducted research on the effectiveness of postponing surgery for femoral neck fractures in children for a 24-hour period. They have also examined the factors that influence the risk of complications. The findings indicate that delayed reduction and fixation of the femur neck yield better results compared to the open reduction group. Additionally, fractures located closer to the femoral head and older age are correlated with an increased occurrence of AVN [25]. However, more scholars have concluded that open reduction does not aggravate the disruption of the blood supply of the femoral head and denied that the method of reduction is a risk cause for AVN after studying a large sample size (more than 70 cases) [26, 27]. Further literature analysis has concluded that open reduction and internal fixation is more accurate in reducing and fixing the fracture, with better clinical and functional outcomes, and lower complication rate [2].

An analysis was conducted on a pair of 686 pediatric patients who had proximal femur fractures, as well as 203 patients with avascular necrosis (AVN) from 21 articles. The analysis focused on examining the clinical and radiological characteristics of these patients. The mean interval of progression to AVN was 13.7±9.5 months. After being diagnosed with AVN, 59.1% of individuals had no symptoms, but 65.2% of cases eventually experienced collapse [28].

Although this study is a retrospective study, the baseline data such as the duration between the injury and the surgical procedure, the follow-up time, and the quality of fracture reduction in the two groups of children was examined, and the differences were found to be statistically insignificant and equivalent. The findings indicated that the observation group was able to significantly reduce the amount of X-ray exposures during surgery and the number of guide pin placements when nailing was performed under robotic navigation. In the observation group, the first postoperative X-ray showed a notable improvement in the parallelism and distribution of screws, in comparison to the control group. These differences were of statistical significance. The duration of the procedure in the observation group was somewhat longer than that in the control group, which was related to the time-consuming operations such as the debugging of the robotic navigation equipment, the acquisition of images, and the planning of screw placement paths, etc. In fact, the time consumed during the period from the insertion of the guide pin to the completion of the insertion of the hollow screws in the observation group was less than that of the control group, which was reflected by the number of exposures and the amount of times of insertion of the needles. Nevertheless, the disparity in total operation time between the two groups did not exhibit any statistically significant variation.

AVN is considered to be the most devastating and common postoperative complication that often follows femoral neck fractures in children. It typically arises as a result of additional issues, such as early closure of the growth plate, the use of hip implants, or the shortening of the limb. The most important factor contributing to AVN is the extent of vascular damage sustained during the traumatic event, which is directly linked to the extent of initial displacement of the fracture and the classification of fracture; on the other hand, it may be related to medical interventions such as the duration between the injury and the surgical procedure, surgical protocols, and methods of immobilization [10]. AVN in children can usually be detected within 1 year after surgery, but some studies have reported that it may appear two or more years after injury [29]. In this study, every patient was monitored for a duration exceeding two years, which is a long-term efficacy observation. The study results showed that the occurrence of complications in the observation group was 31.82%, which was lower than the 48.48% in the control group. Nevertheless, the difference between the two groups did not reach statistical significance. The authors suggest that the absence of a meaningful outcome may be ascribed to the study's small sample size.

It is worth stating that premature epiphyseal closure is a unique complication of femoral neck fracture in children resulting from epiphyseal injury, but whether the hollow screws need to be fixed through the epiphysis in order to assure the stability of the fractured end of the femoral neck is a controversial topic, and it is generally believed that children under the age of 10 who wear epiphyseal fixation will increase the risk of premature epiphyseal closure [30]. In the present study, some patients aged 11–16 underwent intraoperative epiphyseal fixation with hollow screws to ensure solid fixation of the fracture ends, and no cases of premature epiphyseal closure or hip endosteolysis occurred during the follow-up period.

The recovery of hip function in children was correlated with whether the femoral neck fracture healed or not, whether complications occurred or not, and the severity of complications. In this study, at the last follow-up, the observation group had a considerably higher rate of excellent hip function according to the Ratlif criterion (90.91%) compared to the control group (78.79%), and the difference was statistically significant, indicating that robotic-guided nailing was favorable to the recovery of their hip function.

Conclusion

In conclusion, the therapy of children's femoral neck fracture under robotic navigation can realize more accurate screw placement, reduce radiological damage and secondary damage to the fracture, while not increasing the surgical operation time. It can also reduce the occurrence of complications of Delbet type II pediatric femoral neck fracture to a certain extent and promote the rehabilitation of hip joint function, which has a good therapeutic effect. However, so far, there is no high-quality prospective randomized controlled trial and longer-term follow-up to further validate the superiority of this technique, which is the next focus of our work.

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Author contributions
Zhaoxiong Shen and Zhenjiang Liu: study design and article writing; Zhaoxiong Shen, Yongge Chen and Yueming Guo: surgical operation and study implementation; Zhaoxiong Shen and Zhihong Mo: data collection, organization and statistical analysis; Junqing Gao, Feng Wu and Chulong Shen: reviewing and revising.All authors reviewed the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
The study protocol was approved by the Ethics Committee of Foshan Hospital of Traditional Chinese Medicine, Guangzhou Medical University (KY [2023] 112), and informed consent was obtained from the children and their families.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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