Original Clinical Article

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Dimensions of the paediatric femur: anatomical limitations of flexible intramedullary nailing

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Abstract

Purpose Although spica casting remains the benchmark for treating diaphyseal femur fractures in preschool children, some authors advocate using flexible intramedullary nails in certain situations. The aim of the current study was to evaluate the anatomic feasibility of flexible nailing in young children.

Methods Consecutive patients between the ages of zero and ten years with normal femurs who received femur radiographs at a tertiary paediatric hospital over a two-year period were included. Anteroposterior femur radiographs were evaluated for length and isthmus width measurements. Each femur was templated for flexible nail size. The proportions of each age group capable of accommodating two flexible nails up to 4.0 mm in size were determined and compared.

Results A total of 381 full-length femur radiographs were reviewed. There was a strong, direct linear relationship between age and femoral length (R^2 = 0.896) and a moderate correlation between age and femoral isthmus width (R^2 = 0.417). Although the percentage of femurs able to accommodate flexible nails continued to increase with age, this increase did not represent a significant difference when comparing preschool-aged children with older age groups.

Conclusions Age and femoral length demonstrated a strong, positive correlation while age and isthmus width had weaker correlation. The ability of femurs to accommodate flexible nails increased with age with most children age two years and older able to accommodate two flexible nails of at least 2.5 mm in size.

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Keywords: paediatric femoral shaft fracture; flexible intramedullary nailing; femur growth; femoral isthmus width; femoral shaft fracture in preschool-aged children

Introduction

Paediatric diaphyseal femur fractures are commonly managed according to an age-based algorithm in which young children between the ages of six months and six years are treated with immediate spica casting while school-aged children between the ages of six and ten years are frequently treated with flexible intramedullary nail fixation.[1-3] Flexible intramedullary nailing (FIN) has been widely employed and extensively studied for the treatment of paediatric femoral shaft fractures in school-aged children.[4-7] The upper limits of FIN have been established based on anatomical considerations with many authors recommending 50 kg as the maximum weight limit for this treatment modality.[8-11] The lower age limit for FIN is currently a topic of controversy and has yet to be conclusively defined.[12] Immediate spica casting is a well-established treatment for femur fractures in the preschool age group; however, the burden of care to the patient's family and complications associated with this treatment have led some authors to explore the application of FIN to children in this younger age group.[13-17] While several authors have noted satisfactory outcomes of FIN in preschool-aged children, there are no studies that establish the anatomical limitations to FIN in young children.[3,12,18,19] The senior author (MJH) had several cases in young children where flexible nailing was planned; however, preoperative templating revealed that the femoral anatomy could not adequately accommodate sufficiently sized intramedullary nails and spica casting was therefore performed. These cases in combination with the recent interest in utilizing flexible intramedullary nails in young children provided the impetus for the current study.

The aims of this study were to assess the anatomical feasibility of FIN for preschool-aged children and to evaluate the longitudinal and isthmic growth of the paediatric

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femur. Additionally, we sought to compare templated intramedullary nail size in the preschool-age group to the school-age group in whom intramedullary nailing is already well established. We hypothesized that femoral length, isthmus width and the ability to accommodate flexible nails would be closely correlated with chronological age.

Materials and methods

Study protocol

After institutional review board (IRB) approval, a retrospective chart review was performed on consecutive children aged zero to ten years who received full-length femur radiographs at a tertiary paediatric referral centre between June 2012 and October 2014 (IRB #8889). Patients were excluded if their radiographs demonstrated acute fracture, tumour, dysplasia or postoperative changes. Demographic data were collected and included age, gender and laterality of the radiographs.

All femur radiographs were obtained using the Optima XR646 digital radiography unit, (General Electric, Boston, Massachusetts). The images were sent to the Synapse picture archiving and communications system (PACS) (Fujifilm, Tokyo, Japan). Measurements were performed on the Synapse PACS transmitted imaging system (Fujifilm, Tokyo, Japan). Because of the x-ray technique, transmitted images could be aggrandized between 0% and 5%.[20]

Femoral length measurements were performed using the Synapse PACS software by measuring the distance from the centre of the femoral head to the distal-most point along the articular surface of the lateral femoral condyle on full-length anteroposterior femur radiographs. Isthmus width measurements were obtained by measuring the width of the medullary canal at its narrowest site along the isthmus on full-length anteroposterior and lateral femur radiographs. To objectively confirm that the isthmus was correctly identified as the narrowest diameter of the medullary canal, we compared this measurement to the medullary canal diameters measured 1 cm proximal and distal to the location identified as the femoral isthmus.

Each femur was templated for flexible nail size by multiplying the femoral isthmus width measurement by 40%.[20] The proportions of femurs in each age group capable of accommodating two size 2.0-mm, 2.5-mm, 3.0-mm, 3.5-mm and 4.0-mm nails were then determined. Age group comparisons were made by referencing proportions associated with the 2.5-mm nail size. This flexible nail size was selected because it was the most common nail size in previous reports of FIN in young children with satisfactory clinical and radiographic outcomes.[18] To our knowledge, Bopst et al[18] are the only authors to report the specific nail sizes used in the preschool age group.

Statistical analysis

The chi-squared test was used to compare categorical variables (i.e. the ability to accommodate flexible nails of a given size). When the sample size was small, Fisher's exact test was used instead to compare categorical variables. Linear regression analysis was performed to evaluate for correlation between age and femoral length as well as age and femoral isthmus width. The statistical significance level was set at $p < 0.05$.

Results

After application of exclusion criteria, including the age restriction, 381 femur radiographs were included for review. Demographic data are summarized in Table 1.
Table 2 displays the proportion of children by age capable of accommodating two flexible nails of a given size (2.0 mm, 2.5 mm, 3.0 mm, 3.5 mm and 4.0 mm). The majority (85.4%) of children aged two to five years could accommodate 2.5 mm flexible nails. Significantly more

Table 1 Demographic data of study population

Demographic	n (%)
Sex	
Female	143 (41.2)
Male	204 (58.8)
Laterality	
Left	197 (51.7)
Right	184 (48.3)
Age (yrs)	
0	27 (7.1)
1	40 (10.5)
2	48 (12.6)
3	41 (10.8)
4	33 (8.7)
5	36 (9.4)
6	41 (10.8)
7	25 (6.6)
8	26 (6.8)
9	32 (8.4)
10	32 (8.4)

Table 2 Proportions of children by age capable of accommodating two flexible nails of a given size (2 mm, 2.5 mm, 3 mm, 3.5 mm, and 4.0 mm).

	Proportion (%) able to accommodate two nails of at least 'x' size				
Age (yrs)	≥ 2 mm	≥ 2.5 mm	≥ 3 mm	≥ 3.5 mm	≥ 4 mm
0	18.5	0.0	0.0	0.0	0.0
1	70.0	25.0	7.5	0.0	0.0
2	79.2	75.0	39.6	16.7	2.1
3	100.0	87.8	65.9	19.5	4.9
4	100.0	87.9	54.5	27.3	3.0
5	100.0	94.4	80.6	41.7	8.3
6	97.6	95.1	68.3	34.1	22.0
7	100.0	96.0	80.0	68.0	32.0
8	100.0	92.3	84.6	57.7	30.8
9	100.0	96.9	93.8	68.8	40.6
10	100.0	100.0	87.5	50.0	25.0

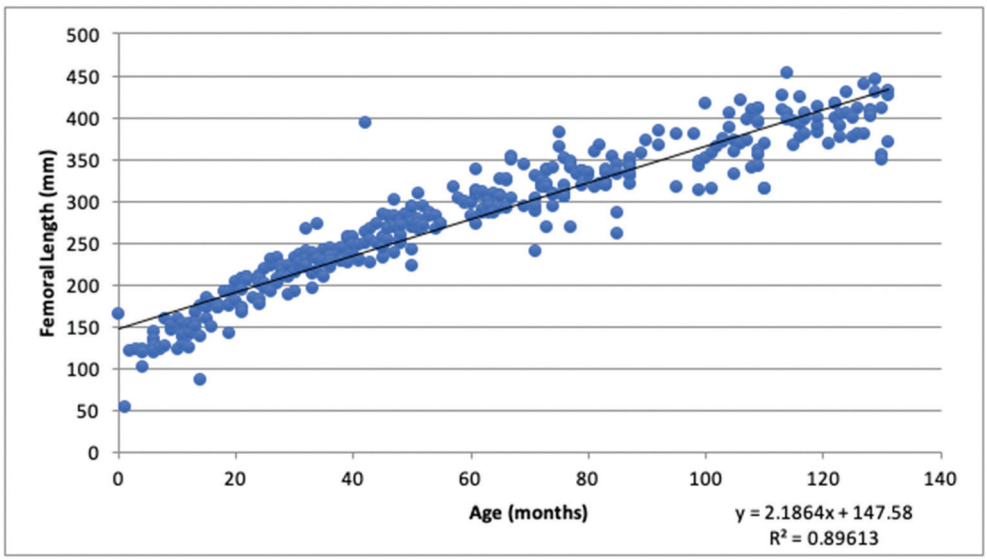

Fig. 1 Distribution of age and femoral lengths for children aged zero to ten years.

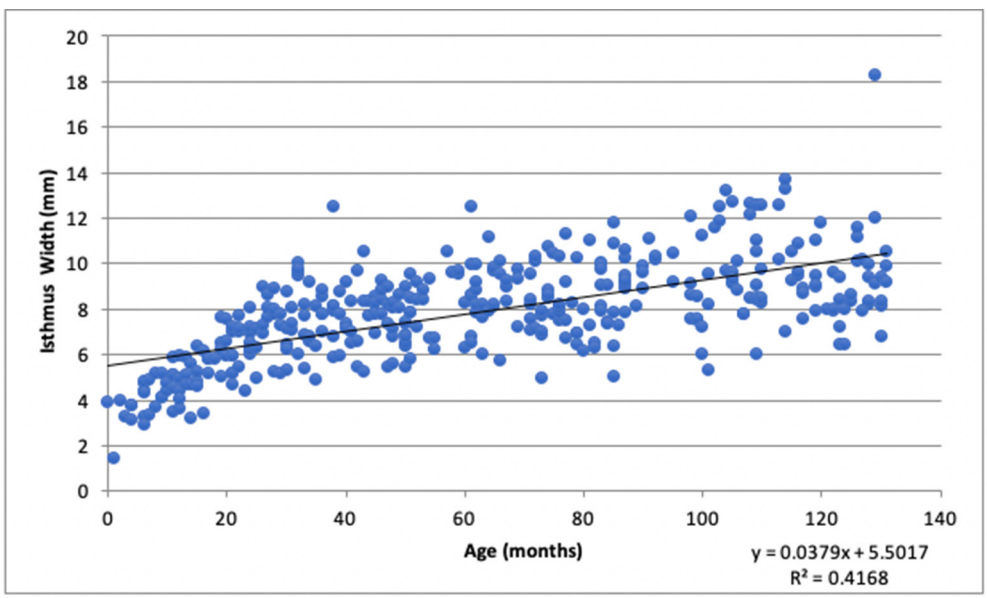

Fig. 2 Distribution of age and femoral isthmus width measurements for children aged zero to ten years.

two-year-olds could accommodate flexible nails of at least 2.5 mm in size compared with one-year-olds (75% *versus* 25%; $p < 0.00001$). These data represent an inflection point between the one-year-olds and two-year-olds for the ability to accommodate 2.5-mm flexible nails, thereby establishing an anatomic cutoff age at two years. The proportion of three-year-olds capable of accommodating flexible nails of at least 2.5 mm in size was not significantly different from that of the six-year-olds (87.8% *versus* 95.1%; $p = 0.236$). The proportion of preschool-aged children (ages three to five years) capable of accommodating flexible nails of at least 2.5 mm in size did not differ from that of the six-year-olds (90% *versus* 95.1%; $p = 0.318$). Though there was a trend towards increasing ability to accommodate 2.5 mm nails with increasing age, no significant difference was noted between preschool-aged children and younger school-aged children (ages six to eight years; 90% *versus* 94.6%; $p = 0.232$). However, when the entire school-aged cohort (ages six to ten) was included, significantly more school-aged children (ages six to ten years) could accommodate flexible nails of at least 2.5 mm compared with preschool-aged children (96.2% *versus* 90%; $p = 0.043$). When evaluating the relationship between age and femoral length, a strong, positive linear relationship was seen

(y = 2.186x + 147.58; R^2 = 0.90; Fig. 1). In contrast, only a moderate correlation was seen between age and isthmus width (y = 0.0379x + 5.5017; R^2 = 0.42; Fig. 2). Of note, minor differences between mean anteroposterior and lateral isthmus width measurements for each age group between ages zero and five years did not achieve statistical significance. In all, 68.0% and 93.8% of children between the ages of 0 and five years had anteroposterior and lateral femoral isthmus diameter differences of 1.0 mm and 2.0 mm or less, respectively.

Discussion

To our knowledge, this is the largest study in recent years examining femoral longitudinal growth and the first to describe the growth of the femoral isthmus. Since FIN relies on measuring the femoral isthmus to determine implant size, understanding the growth pattern of the femoral isthmus during childhood is critical in determining the anatomical limitations of this treatment option at the lower limits of the patient size continuum. In recent years, there has been a growing interest in the application of FIN for the treatment of femoral diaphysis fractures in younger children. The current study supports FIN as an anatomically feasible treatment option for preschool-aged children with these fractures.

Over the past three decades, there has been a shift away from spica cast treatment of diaphyseal femur fractures in school-aged children in favour of FIN.[21-23] A prospective study performed by Flynn et al[24] supported the benefits of FIN over traction with spica casting in the treatment of diaphyseal femur fractures in children between the ages of six and ten years. Further studies confirmed excellent outcomes with FIN of femoral shaft fractures in school-aged children.[4-7] As the use of flexible intramedullary nails became more mainstream, authors began exploring the limitations of this treatment modality at the upper end of the patient size continuum. Heavier patients were found to have increased malunion rates and worse clinical outcomes, and a 50 kg maximum weight limit was established for FIN of femur fractures.[8-11] Despite the widespread adoption of FIN for the treatment of femur fractures in school-aged children, the benchmark for the management of these fractures in the preschool-age population remains spica casting and little change in national practice patterns has been observed over the past three decades with respect to this age group.[2,3,21-23] In recent years, however, several authors have explored the application of FIN in the management of femoral shaft fractures in younger patients.[3,12,18,19] These studies have largely found FIN to have comparable clinical and radiographic outcomes with spica casting and have largely supported FIN to be a reasonable alternative to spica casting for select patients in the preschool age group. A clear disadvantage of FIN is the second surgery for implant removal as well as the potential risk for neurovascular complication or infection.[3] In contrast, advocates of FIN note the benefits of avoiding cast-related complications such as skin breakdown and compartment syndrome as well as the relative ease of patient care for the family. Hughes et al[25] found that parents took on average three weeks off work in order to care for a child in a spica cast as these children were not permitted to return to daycare or school in the cast. FIN has previously been applied to treat femur fractures in polytraumatized preschool-aged patients with satisfactory results. Pollak et al[26] demonstrated that spica casting was less effective in maintaining femur reduction after higher energy mechanisms of injury. Heffernan et al[3] demonstrated satisfactory clinical and radiological outcomes in a group of children with femur fractures treated by FIN, many of whom sustained polytrauma injuries as a result of a high energy mechanism of injury. Although these studies support the utility of FIN in certain situations in this younger age group, the current study is the first to focus on how anatomical limitations of these children could restrict use of this treatment option.

We assessed femoral growth between the ages of zero and ten years and found a strong, direct linear relationship between age and femoral length with an average femoral growth rate of 2.6 cm per year (y = 2.186x + 147.58; R^2 = 0.90). These findings are comparable with prior studies, particularly those by Anderson et al[27-30] whose data on paediatric femoral growth, when plotted, also revealed a strong, linear relationship between age and femoral length with an average longitudinal growth rate of 2.4 cm per year between the ages of zero to ten years. To the best of our knowledge, the current study was the first to evaluate the growth of the femoral isthmus. We noted there was moderate correlation between age and isthmus width (y = 0.0379x + 5.5017; R^2 = 0.42). The finding that age only moderately reflects femoral isthmus width was unexpected but enlightens our understanding of treatment feasibility in young children. Based on this finding, preschool children may be able to anatomically accommodate flexible nails since age does not closely reflect the isthmus size.

We used the templating method of multiplying the femoral isthmus by 40% to determine the preferred flexible nail size as described by Lascombes et al.[20] The vast majority (90%) of preschool-aged femurs (ages three to five years) in our population could accommodate two flexible nails of at least 2.5 mm in size. This finding was not significantly different from the proportion of six-year-olds capable of accommodating 2.5-mm flexible nails (90% *versus* 95.1%; p = 0.318) nor was it different from the proportion of younger school-aged children able to accommodate two 2.5-mm nails (90% *versus* 94.6%; p = 0.232). Our study

finding that there was no significant difference in the ability of preschool-aged children to accommodate 2.5-mm flexible nails compared with younger school-aged children supports our hypothesis that FIN is anatomically feasible in the preschool age group. The age cutoff for anatomic feasibility of FIN appears to be two years, as 75% of two-year-olds could accommodate 2.5 mm nails compared with only 25% of children between the ages of 12 and 23 months ($p < 0.00001$). Only one study on FIN femoral shaft fractures in preschool-aged children detailed the nail sizes used.[18] The vast majority of femur fractures (67.1%) were treated with 2.5-mm flexible nails and none required supplementary stabilization with a cast or brace.[18] Furthermore, these authors described satisfactory clinical and radiographic outcomes without increased morbidity of FIN over spica casting and deemed FIN to be an acceptable treatment option for the management of femur fractures in preschool-aged children.[18] The 2.5-mm nail size was therefore selected as the cutoff nail size for determining the anatomic feasibility of FIN in preschool-aged children in this study. Table 2, however, lists the proportions of each age group capable of accommodating two flexible nails of sizes varying from 2.0 mm up to 4.0 mm. More biomechanical studies are needed evaluating weight limitations for each flexible nail size, and this may be an area in which to direct future research efforts as childhood obesity rates continue to rise.

Limitations of this study include its design as strictly a retrospective review of radiographs. The fact that the templated nail size was never confirmed by *in vivo* implantation leaves the possibility for discordance between templated and actual implantable nail size. Another source of variability is that the femoral isthmus is visually identified as the narrowest site in the medullary canal. Due to the oval shape of the isthmus, variability could be introduced by rotational position of the femur. To improve the accuracy of our isthmus identification, we measured the visually identified isthmus width as well as the width of the medullary canal 1 cm proximal and distal to this site to confirm the isthmus measurement as the narrowest. Additionally, we measured the isthmus in both the anteroposterior and lateral radiographs to minimize error. A final source of error is the possibility of aggrandizement of the images depending on the size of the soft-tissue envelope of the thigh. Since no size reference (e.g. marker ball) was used to scale the digital ruler, measurements taken with the digital ruler may not account for subtle magnification variances due to the elevation of the femur off the radiographic cassette by soft-tissue envelops of differing thicknesses.

Conclusion

Ultimately, this study reaffirms the positive, nearly linear association between age and femoral length observed in prior studies.[27-30] Surprisingly, age and femoral isthmus width were only moderately correlated, and the anatomical lower limit for FIN determined in this study does not coincide with that established by the traditional age-based algorithm. Based on our study population, a vast majority of children over the age of two years could accommodate flexible nails of size 2.5 mm. Furthermore, similar proportions of preschool-aged children and younger school-aged children could accommodate nails of this size. Therefore, we conclude that FIN is a viable treatment option for diaphyseal femur fractures in preschool-aged children from a strictly anatomical standpoint. It is important to note that good clinical judgement and not anatomical feasibility guide patient care decisions. Specific factors, of course, must be taken into consideration by the treating surgeon in deciding upon the optimal treatment approach for each unique child.

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COMPLIANCE WITH ETHICAL STANDARDS

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Ethical approval: This study was approved by the institutional review boards of the Louisiana State University School of Medicine as well the Children's Hospital New Orleans.

Informed consent: Informed consent was not required.

ICMJE CONFLICT OF INTEREST STATEMENT

None of the authors have any conflict of interest to declare.

AUTHOR CONTRIBUTIONS

TL: study design, performed measurements, statistical analysis, manuscript preparation.
SR: study design, performed measurements, manuscript preparation.
AA: performed measurements, manuscript preparation.
LI: performed measurements, manuscript preparation.
MJH: study design, data analysis, manuscript preparation.

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