



## RESEARCH ARTICLE

# Biomechanical Characteristics of the Femoral Isthmus during Total Hip Arthroplasty in Patients with Adult Osteoporosis and Developmental Dysplasia of the Hip: A Finite Element Analysis

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**Objective:** This study investigated the underlying mechanisms of high fracture incidence in the femoral isthmus from a biomechanical perspective.

**Methods:** We retrospectively analyzed a total of 923 primary total hip arthroplasty (THA) patients and 355 osteoporosis (OP) patients admitted from January 2010 to January 2018. Through a series of screening conditions, 47 patients from each group were selected for inclusion in the study. The datasets on the unaffected side and affected side of the patients with unilateral developmental dysplasia of the hip (uDDH) were respectively classified as the normal group (Group I) and the tDDH group (Group II), and that of patients with osteoporosis were classified as the OP group (Group III). In this study, first, we collected computed tomography (CT) images and measured geometric parameters (inner and outer diameters) of the isthmus. Thereafter, to study biomechanical properties, we established six finite element models and calculated values of von Mises stress for each group with the methods of data conversion and grid processing.

**Results:** Compared with those of patients in the normal group, the values of the inner and outer diameters of femoral isthmus of patients in the DDH group were significantly lower ( $P < 0.001$ ), while the inner diameters of patients in the OP group were significantly higher ( $P < 0.001$ ) and the outer diameters of patients in the OP group showed no significant difference ( $P > 0.05$ ). The cortical rates of patients in the normal group and the DDH group appeared insignificant ( $P > 0.05$ ), and those of patients in normal group were significantly higher than those of patients in the OP group ( $P < 0.001$ ). Moreover, patients in the DDH group showed a higher von Mises stress value than patients in the normal group ( $P < 0.001$ ), but statistically speaking the values between patients in the OP and normal groups were insignificant ( $P > 0.05$ ).

**Conclusions:** The relatively shorter inner and outer diameters of the isthmus in DDH resulted in intensive von Mises stress under the torque of the hip location, and induced a high fracture incidence. However, in patients in the OP group, the geometric morphology exhibited no anatomical variation, and the fracture was not due to the intensity of von Mises stress.

**Key words:** Developmental dysplasia of the hip; Finite element analysis; Intraoperative femoral isthmus fracture; Osteoporosis; Total hip arthroplasty

## Introduction

Currently, total hip arthroplasty (THA), which serves as an effective treatment for patients with hip pain and

dysfunction, has been lauded as “the operation of the century” by *The Lancet*;<sup>1</sup> by 2030, only in the United States would the demand for THA increase by 174% from 2005 to

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572,000.<sup>2</sup> However, its various complications, which result in a high risk of revision surgery and are accompanied by high morbidity rates, are still problems to be studied.<sup>3-5</sup> Fractures account for a large proportion of complications during THA and may cause infection and atrophic nonunion.<sup>6,7</sup> As one of the complications of THA, periprosthetic femoral fractures (PFFs) have been reported to have an increasing incidence in recent years, probably due to previous revision arthroplasty surgeries, and the presence of rheumatoid arthritis.<sup>8,9</sup> According to clinical observations, it is common that in patients with adult developmental dysplasia of the hip (DDH) and osteoporosis (OP), the femoral shaft is prone to fracture because of strong torsion and hammering during THA and the fracture incidence of the femoral isthmus is much higher than that of THA for healthy adults. Therefore, surgeons have been concerned about what actions would not induce fractures, and which site had the weakest biomechanical stability after reconstruction. Meanwhile, it is surprising that no studies have been conducted to explain the reasons for fractures in the isthmus from a biomechanical perspective.

For DDH patients, deformities of the femur and acetabulum cause higher fracture rates during the surgical exposure, dislocation and installation of prostheses because of the anatomical characteristics.<sup>10,11</sup> Currently, it is recognized that the main reasons for fracture are the improper practice and the difference in stiffness between the bone and implant.<sup>12</sup> OP is also a predisposing factor for the intraoperative fracture in the femoral isthmus because of the reduction in bone density and deterioration of bone microarchitecture.<sup>13-15</sup> OP has been reported as the major cause of an estimated nine million osteoporotic fractures.<sup>16</sup> Previous studies showed that the rate of subsequent fracture decreased by 50% in patients who received osteoporosis treatment.<sup>17</sup>

Therefore, we expect to find that the mechanism of fractures in the isthmus can play a significant role in preventing intraoperative accidents caused by orthopedic surgeons. A wide range of previous studies on fractures of THA typically focus on clinical research, such as risk factors for fracture including bone quality, age and comorbidities; however, power reamers, mismatched prostheses and forceful practice can also lead to intraoperative fractures.<sup>18-21</sup> However, basic biomechanical studies are apparently limited and most of them entail ordinary mechanical experiments that are not suitable for the human body.<sup>22-24</sup> Finite element analysis (FEA), which has become an effective method for femur biomechanical analysis, can exactly simulate intraoperative dislocation and fractures during THA.<sup>25,26</sup>

Since no study has revealed the mechanism for fractures in the isthmus of patients with DDH and OP during THA, the purpose of our study was: (i) to explore the reasons for the higher fracture incidence rate of patients with DDH and OP, and demonstrate the morphological characteristics in the isthmus by three-dimensional reconstruction; and (ii) to analyze their biomechanical properties with finite element models and provide reference for clinical operation. To achieve the above two research purposes, we

hypothesized that the morphological characteristics of the femoral isthmus in patients with DDH and patients with OP exhibited significant differences compared with the characteristics of a healthy femoral isthmus. Moreover, this morphological feature could result in a relatively high and intensive stress in the femoral isthmus of patients with DDH and patients with OP during THA. Clarifying this relationship would be meaningful for the prevention of femoral isthmus fracture. Hopefully, the present study findings will encourage clinicians to be aware of the range and strength of actions influencing hip location when performing THA for DDH and OP patients.

## Materials and Methods

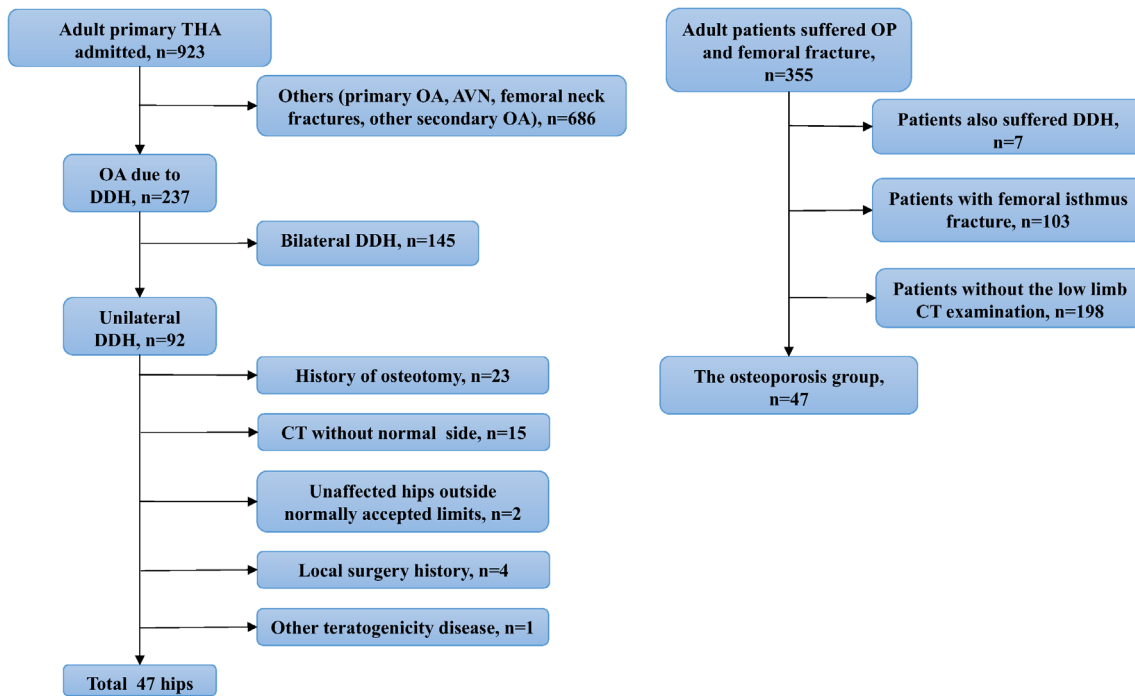
### Inclusion and Exclusion Criteria

Inclusion criteria were: all of the patients was retrospectively reviewed to identify adult patients who had undergone THA for the treatment of secondary osteoarthritis due to unilateral developmental dysplasia of the hip (uDDH) and who had preoperative images, including standard anteroposterior radiographs and CT scans. Exclusion criteria were: (i) the identified patients were screened for eligibility using the following exclusion criteria: bilateral DDH, prior pelvic or femoral osteotomy; (ii) CT images only of the affected hip (without the reference of the unaffected hip); (iii) the morphological features of the unaffected hip that were outside normally accepted limits, with a healthy hip defined by the absence of osteoarthritis and pain, a center-edge angle of  $>25^\circ$ , and a sharp angle of  $>45^\circ$ ; and (iv) local surgery history and the other with teratogenic disease.

### Patients

The study protocol was approved by the review board of The First Affiliated Hospital of Xi'an Jiaotong University, and informed consent was obtained from all patients. All investigations were conducted in conformity with ethical principles of research, and the ethical approval number was 2008132476.

We retrospectively analyzed a total of 923 primary THA patients admitted to the Department of Orthopedics of The First Affiliated Hospital of Xi'an Jiaotong University, Department of Orthopedics of The Second Affiliated Hospital of Xi'an Jiaotong University and Honghui Hospital from January 2010 to January 2018. After screening, the 47 patients with uDDH entered into our analysis. The datasets on the unaffected side and affected side of the 47 patients with unilateral developmental dysplasia of the hip (uDDH) were respectively classified as the normal group (Group I) and the DDH group (Group II), and that of patients with osteoporosis were classified as the OP group (Group III). A total of 355 cases were selected from patients who received bone mineral density (BMD) examinations for OP from the Picture Archiving and Communication Systems of The First Affiliated Hospital of Xi'an Jiaotong University, The Second Affiliated Hospital of Xi'an Jiaotong University and Honghui Hospital from January 2010 to January 2018. Identified



**Fig. 1** The flow diagram of the selection of adult unilateral developmental dysplasia of the hip (uDDH) patients and the adult osteoporosis for analysis. THA, total hip arthroplasty; OA, osteoarthritis; AVN, avascular necrosis of the femoral head; CT, computed tomography; OP, osteoporosis; BMD, bone mineral density

patients were screened for eligibility using the following exclusion criteria: patients with both OP and uDDH; with femoral isthmus fracture; and without a lower limb CT examination (Fig. 1).

### Parameters Measurement

The CT scans were performed using a TOSHIBA Aquilion 320 spiral CT scanner (Toshiba, Tokyo, Japan). The tube voltage was 120 kV, the current was automatic, and the pixel-matrix was  $512 \times 512$ . The thickness of each slice was 1.0 mm, and the interval between the slices was 1.0 mm. The scans were performed from the iliac crest to the distal one-third of the femur. The patients were in a supine position with the bilateral lower limbs positioned such that they had 15 degrees of internal rotation. Every retrospectively selected patient was scanned on the same scanner. All the scan data were attained in DICOM format from the CT Picture Archiving and Communication Systems of The First Affiliated Hospital of Xi'an Jiaotong University. The osteophytes around each femoral head were removed. The coordinate of the center of the femoral head was then established. The inner diameters (IDs) and outer diameters (ODs) of the osteotomy surface in the femoral isthmus were repeatedly measured from the mediolateral dimension according to the information reported by Husmann *et al.*<sup>27</sup> The cortical rate (CR) was calculated with Equation (1):

$$CR = (OD - ID) / OD. \quad (1)$$

### Finite Element Modeling

First, each data point from CT scans was selected randomly from normal group patients and exported into the Mimics 17.0 (Materialise, Leuven, Belgium) for reconstruction, and the bone model was extracted from the 3D model. The data of the 3D reconstruction were deposited in STL format. In addition, the STL data were exported to the Geomagic Studio 12.0 for further processing, and the data were saved in STP format. Third, the STP data were exported into the Pro/E 5.0 to organize the primary model and the outcome was deposited in IGES format. Finally, the IGES format data were exported in Hyperrmesh 12.0 for finite element grid processing. Then, the contralateral healthy femur model was successfully established. Based on the normal femur model, we established an ideal adult uDDH femoral model and OP femoral model by adjusting the parameters of the femoral isthmus (Table 1). In this process, the parameters of the other parts were also controlled to be equal. The flow diagram of establishing the model is shown in Fig. 2. In the finite element model, through the morphing operation, the mesh is automatically adapted to the surface of the 3D model, thereby ensuring the consistency of the mesh.

**TABLE 1** The comparison of geometric parameters among three groups

	Cortical bone cross-sectional area (mm <sup>2</sup> )	Cortical bone thickness (mm)
Group I model	478	8
Group II model	478 × 0.7	8
Group III model	478 × 0.7	4.6

The material parameters and the number of nodes and elements of the femur were recorded (Table 2). All models used the same nodes and elements. We adopted the bone tissue with isotropic linear elastic materials, and their known Poisson's ratio and elastic modulus were assumed for subsequent calculations. The cell type was the C3D8I hexahedral mesh. Both the cortical bone and the cancellous bone were adopted in our analysis of the hexahedron element because its calculation accuracy is higher than the tetrahedron element. The tetrahedral element type is a constant-strain element, which means that the element has only one stress and strain with no stress gradient, while the hexahedral element is a gradient element. As long as it is not a reduced integration element (therefore, C3D8I is used in this article), there can be multiple stress and strain integration points inside the element, which can be used to accurately describe the

**TABLE 2** The parameters of the finite element model of human femur

	Elastic modulus (MPa)	Poisson's ratio	Number of elements	Number of nodes
Cortical bone	13,700	0.3	85,583	19,682
Cancellous bone	840	0.3	13,426	58,381

gradient change area. This means that if the accuracy is the same, the calculation result of the hexahedron is more suitable to reflect the occurrences in the place where the strain gradient changes.

### Boundary and Loading Conditions

The distal bone was fixed for later torsional loading. The stress point is located on the midline of the inner and outer condyles of the distal femur. The point on the distal femoral surface was coupled with the torque load point to be used to withstand torque loads. All degrees of freedom of the femoral head were restricted. The torque that mimicked the hip dislocation load during the THA was applied to the top surface of the spot perpendicularly for 10 N\*m (Fig. 3(B)). The analysis region is continuously dispersed into several sub-domains, and the elements are connected to each other by nodes on their boundaries. Von Mises stress was introduced to reveal the stress threshold of different models. For isotropic materials, when the internal particle is in a unidirectional stress state that being greater than yielding stress will result in the particle entering yielding state. In each group, FEA was performed on six samples and the maximum von Mises stress was recorded. Thus far, the results of FEA, calculations and their trend of change have been verified by the ring simplified theory.

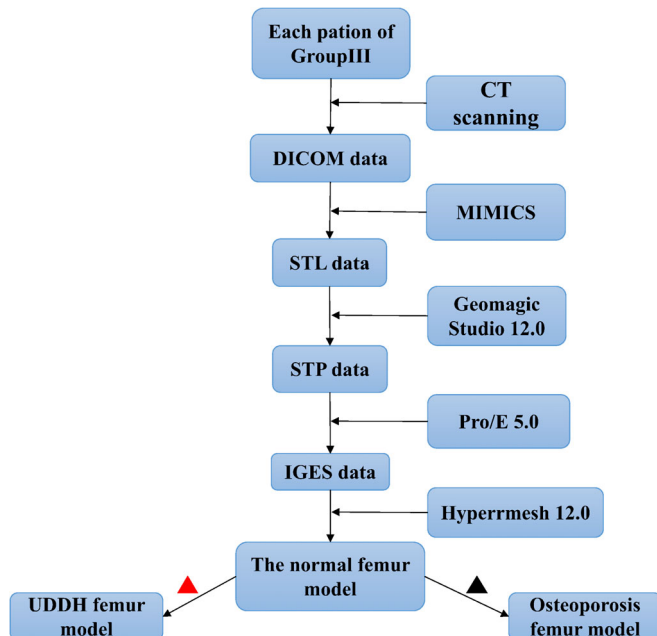
### Statistical Analysis

We applied the ggplot2 package to visualize and analyze the statistical data by R 3.6.3 (<https://www.r-project.org>).<sup>28</sup> All the data are presented as the mean ± standard deviation. The general data and von Mises stress were analyzed by one-way analysis of variance (ANOVA) followed by *post hoc* Tukey's multiple comparison test. The parameters of the isthmus were analyzed by the Kruskal-Wallis test, and then a multiple hypothesis test (Dunn's test) was used to correct the significance level. A *P* value <0.05 was defined as statistically significant.

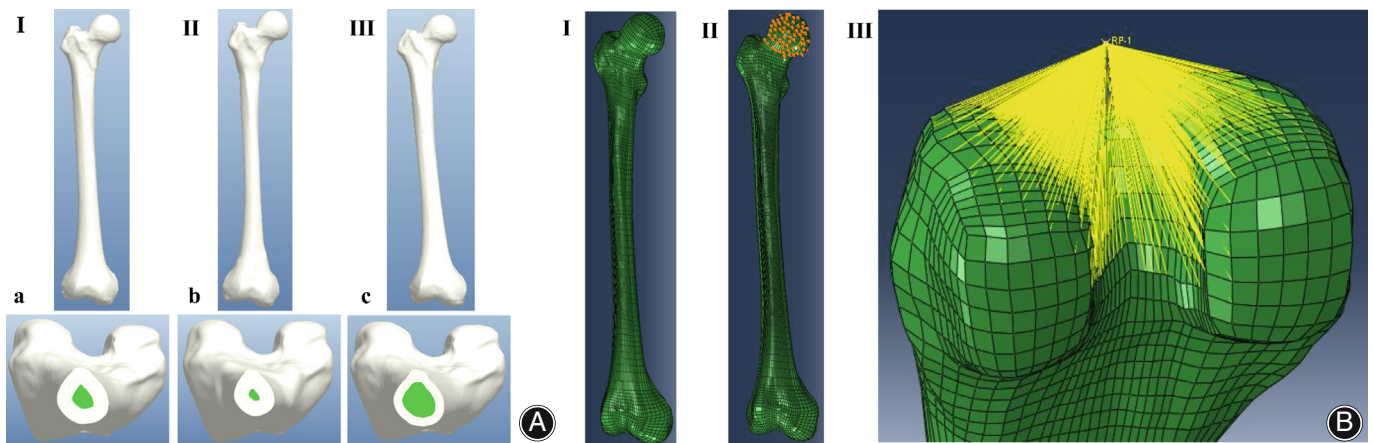
## Results

### General Data

The age of participants was  $48.17 \pm 13.00$  years for those in the normal group and the DDH group, and



**Fig. 2** The flow diagram of establishing the three models. Red triangle, based on the statistical discrepancy between Group I and Group II; Black triangle, based on the statistical discrepancy between Group I and Group III



**Fig. 3** (A) Three-dimensional models of three types of femur. I, the model of unaffected side femur of unilateral developmental dysplasia of the hip (uDDH) (Group I). II, the model of affected side of adult uDDH femur (Group II). III, the model of adult osteoporosis (OP) femur (Group III). a, b, c were the cross-sections of the femoral isthmus of the femoral model. a, b, c was respectively corresponding to Group I, Group II, Group III. (B) Schematic diagram of finite element model. I, the finite element analysis (FEA) mesh model; II, the femoral head was degree of freedom constrain; III, the coupling node boundary of distal femur

49.23 ± 12.08 years for those in the OP group. The body mass index (BMI) was 24.05 ± 2.39 kg/m<sup>2</sup> for participants in the normal and DDH groups, and 24.37 ± 2.45 kg/m<sup>2</sup> for participants in the OP group. There was an insignificant difference in the age and BMI of participants in each group ( $P > 0.05$ ; Fig. 4). Moreover, three femoral models were successfully established (Fig. 3(A)).

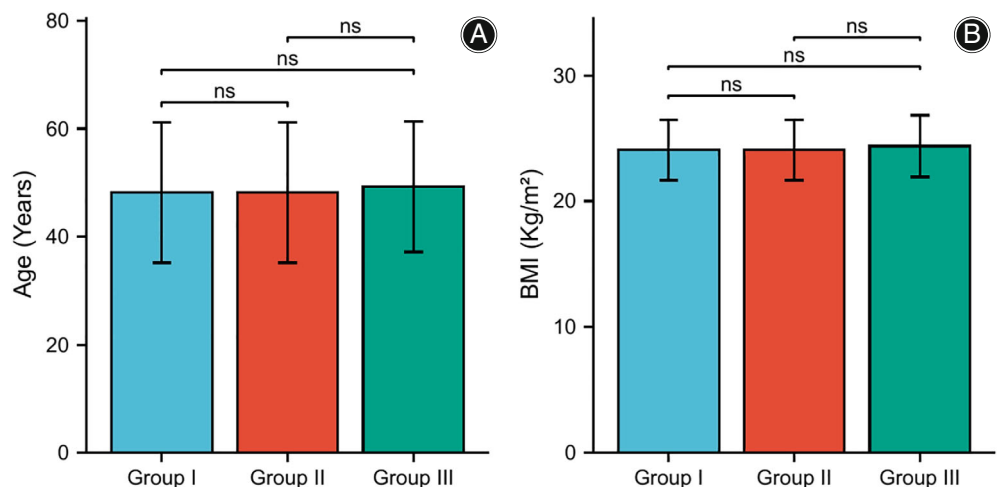
#### Parameters of the Isthmus

The OD, ID and CR of the femoral isthmus were 29.10 ± 3.06 mm, 12.13 ± 1.37 mm and 0.58 ± 0.06 in participants in the normal group; 19.60 ± 1.06 mm, 8.26 ± 0.52 mm and 0.58 ± 0.03 in participants in the DDH group; and 29.97 ± 1.50 mm, 20.20 ± 1.14 mm and 0.32 ± 0.05 in participants in the OP group, respectively. The OD and ID of participants in the DDH group were significantly smaller than those

of participants in the normal group ( $P < 0.001$ ), and the CR of participants in the normal and DDH groups showed insignificant differences ( $P > 0.05$ ). There was no statistical significance in the OD between participants in the normal and OP groups, while the CR of participants in normal group was significantly higher than that of participants in OP group ( $P < 0.001$ ; Table 3).

#### Finite Element Analysis Results

The results of von Mises stress on the femoral model were 0.55 ± 0.13 MPa participants in normal group, 1.09 ± 0.17 MPa in participants in the DDH group and 0.66 ± 0.11 MPa in participants in the OP group. The maximum stress was located at the femoral isthmus and the part surrounded (Fig. 5(A)). The stress on the two ends of the three femoral models was smaller than the stress on the



**Fig. 4** General data of baseline patient. (A) The quantified data of age. (B) The quantified data of body mass index (BMI).

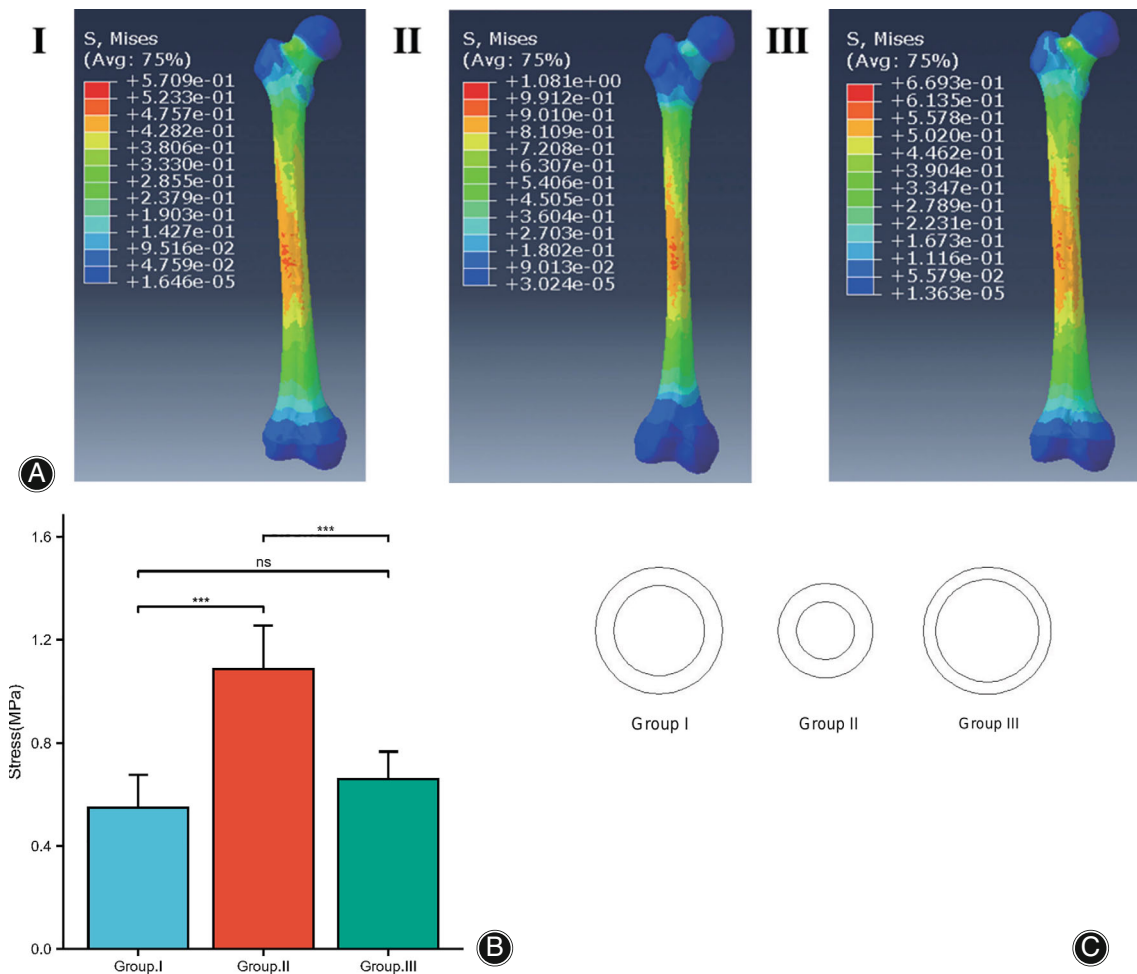
n.s indicates  $P > 0.05$

TABLE 3 The morphology variation of femoral isthmus among the three groups									
	I	II	III	I vs. II		I vs. III		II vs. III	
				z	P-Value	z	P-Value	z	P-Value
OD	29.10 ± 3.06	19.60 ± 1.06	29.97 ± 1.50	-7.554	0.000	1.640	0.303	9.194	0.000
ID	12.13 ± 1.37	8.26 ± 0.52	20.20 ± 1.14	-5.561	0.000	5.591	0.000	11.151	0.000
CR	0.58 ± 0.06	0.58 ± 0.03	0.32 ± 0.05	0.104	1.000	-8.315	0.000	-8.419	0.000

Abbreviations: CR, cortical rate; ID, inner diameter; OD, outer diameter.

other parts of the femur. The femoral shaft, excluding the isthmus, underwent relatively minimal stress. Participants in the DDH group showed higher von Mises stress than participants in the normal and OP groups ( $P < 0.00$ ; Fig. 5(B)). According to the material mechanical ring torque calculation

formula, the femoral isthmus of the above three models could be simplified as three rings (Fig. 5(C)). Table 4 shows the ID and OD of three simplified models. We calculated the stress of the three simplified models by using the following Equation (2):



**Fig. 5** (A) The stress distribution on the femur of the three models. I, Group I model; II, Group II model; III, Group III model. (B) The quantified data of Mises stress. (C) The simplified ring model of the isthmus of three groups. n.s indicates  $P > 0.05$  and \*\*\* indicates  $P < 0.001$

**TABLE 4** The ID and OD of three simplified models

	OD (mm)	ID (mm)
Group I model	27.7	19.7
Group II model	20.6	12.6
Group III model	27.7	22.4

Abbreviations: ID, inner diameter; OD, outer diameter.

$$\tau_{\max} = \frac{T \cdot R}{I_p} = \frac{T}{W_p},$$

$$W_p = \frac{\pi \cdot (D^4 - d^4)}{16 \cdot D}. \quad (2)$$

The calculation results of the finite element model (FEM) and simplified model showed that under the load of torque, the von Mises stress of the normal group model was smaller than that of the OP group model, which was again smaller than that of the DDH group model (Table 5). The calculation results of the simplified theoretical model appeared in accordance with the FEM. However, the stress value of the simplified model was smaller than that of the FEM. The reasons for this outcome were that the simplified model was a ring and that the FEM contained the cancellous material, which resisted the torque.

## Discussion

In this retrospective study, the biomechanical properties of the femoral isthmus of uDDH patients and contralateral healthy and OP patients were explored. The most important finding was that, compared with participants with contralaterally healthy uDDH, both uDDH and OP patients exhibited special anatomic characteristics related to the femoral isthmus. Von Mises stress values in the femoral isthmus of the uDDH were significantly higher than those of the contralateral healthy uDDH under torque and was prone to fracture when hip dislocation occurred during THA. Therefore, orthopedists should do their best to eliminate the occurrence of fractures and improve the outcome of surgeries.

**TABLE 5** The comparison of Mises stress between theoretical results and FEA results

	Simplified (MPa)	FEA (MPa)
Group I model	0.322	0.55
Group II model	0.678	1.09
Group III model	0.419	0.66

Abbreviation: FEA, finite element analysis.

## Clinical Significance of Biomechanical Properties

At present, a massive number of studies have reported solutions to various complications resulting from fractures. Trochanteric fractures and superoposterior capsular avulsions occurred during femoral elevation and movement. Therefore, to avoid trochanteric fractures, a second-generation fracture table with an electronic hook elevation system has been established.<sup>29</sup> In addition, PFF is another of the common complications that can be treated by fixation with cerclage wire and generally occurs in the process of inserting the prosthesis stem and reaming the medullary canal.<sup>30,31</sup> However, the literature on the fundamental principles of the biomechanics of fractures is still scarce. This scarcity leads to surgeons having limited knowledge of the application of torque during THA and makes it difficult to reduce the risk of fractures more effectively. Our study fills the gaps in knowledge in this area and provides a clear reference for surgeons to follow during an operation.

## Biomechanical Evaluation of Finite Element Models

Based on the clinical experience, femoral isthmus fractures in patients with DDH and OP are common during THA. In this study, we found that the values of the outer and inner diameters of the femoral isthmus in the DDH patients were lower than those in patients in the normal group, and this special structure resulted in a relatively higher stress concentration and increased susceptibility to torque loads. The special anatomical structure leading to the different stress distribution is one of the most common characteristics among DDH patients. Studies have shown that the acetabular contact pressure among DDH patients significantly increases,<sup>32</sup> the tissue and bone interface excessively twist and shear when walking and standing,<sup>33</sup> and special anatomical structures change the otherwise homogeneous stress distribution of the healthy joint so that the stress concentration moves to the acetabular edge.<sup>34</sup> Bones are anisotropic, which means the bones are naturally loaded axially and move differently depending on which point experiences the stress load. Therefore, the torque can easily cause damage to the femur, especially the isthmus. When the loading rate goes beyond the bearing limitation of the bone and results in a breaking point, the energy released by the fracture site will induce fragmentation and serious soft tissue damage. To avoid the fracture, we should try our best to protect the femoral isthmus while dislocating the hip during THA for DDH patients. The effective release of the capsule of the hip is good for decreasing the fracture risk.

With the OP patients, Power *et al.* demonstrated that reduced cortical bone thickness increases stress and strain in femur.<sup>35,36</sup> However, in this study we found that the cortical rate of the femoral isthmus in OP patients is lower than that among the contralateral healthy isthmus of those with uDDH, while the results of FEA showed that there is no difference between patients and healthy people, which means that the role of stress in isthmus fracture is not obvious. Therefore, the possible reasons for the high fracture

incidence are reduced bone stock and increased bone fragility,<sup>37,38</sup> which may also be related to the limitation of our study because of the small number of samples.

Therefore, generally speaking, many femoral anatomical changes appear in DDH patients. It is difficult to determine that how the change in a single part (femoral isthmus) affects the biomechanical properties. In this study, we adopted the single factor test to reveal the role played by the femoral isthmus in the biomechanical properties. We controlled the parts of the femur excluding the femoral isthmus of the three groups to ensure there was no difference. We established the finite element models of the patients with OP and uDDH on the basis of the contralateral healthy femur of patients with uDDH by changing the parameters of the femoral isthmus of the samples in normal group. On this condition, we conducted FEA to reveal the data of biomechanical variation.

### Limitations

There are several limitations in our study. Discretization of the study area inevitably leaves some uncertainties, and the finite element models only included six samples in each group. Additionally, the studied patients were selected from only three hospitals which may have caused the selection

bias. In further study, we will continue the evaluation on this topic described in this study in multiple centers.

### Conclusions

Our study demonstrated that the value of the outer and inner diameters of the femoral isthmus in DDH patients is lower than that of healthy patients, while the cortical rate of femoral isthmus in OP patients is lower than that of those in normal group. This special anatomical feature of the femoral isthmus of the DDH contributes the stress being intensively distributed in the isthmus, but OP patients showed insignificant differences in biomechanics compared to other participants. Therefore, the higher fracture incidence of DDH is due to the increased strain caused by the morphological structure. To decrease the risk of intraoperative fracture, we should exert more effort to protect the femoral isthmus. The effective release of the hip capsule can successfully decrease the risk of fracture.

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