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

Jianzhong Sun, BS¹², Rupeng Zhang, MD³, Shenghang Liu, BS², Yuqi Zhao, BS²³, Genwen Mao, MD³, Weiguo Bian, MD¹

¹Department of Orthopedics, The First Affiliated Hospital of Xi’an Jiaotong University, ²Xi’an Jiaotong University Health Science Center and ³Department of Orthopedics, The Second Affiliated Hospital of Xi’an Jiaotong University, Xi’an, China

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 DDH 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;¹ by 2030, only in the United States would the demand for THA increase by 174% from 2005 to

Address for correspondence Weiguo Bian, MD, Department of Orthopedics, The First Affiliated Hospital of Xi’an Jiaotong University, 227, Yanta West Road, Xi’an, 710061, Shaanxi, China; Email: doctorbianweiguo@163.com

Received 7 June 2021; accepted 25 July 2022
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.\textsuperscript{3–5} Fractures account for a large proportion of complications during THA and may cause infection and atrophic nonunion.\textsuperscript{6,7} 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.\textsuperscript{8,9} 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.\textsuperscript{10,11} Currently, it is recognized that the main reasons for fracture are the improper practice and the difference in stiffness between the bone and implant.\textsuperscript{12} 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.\textsuperscript{13–15} OP has been reported as the major cause of an estimated nine million osteoporotic fractures.\textsuperscript{16} Previous studies showed that the rate of subsequent fracture decreased by 50\% in patients who received osteoporosis treatment.\textsuperscript{17}

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.\textsuperscript{18–21} However, basic biomechanical studies are apparently limited and most of them entail ordinary mechanical experiments that are not suitable for the human body.\textsuperscript{22–24} Finite element analysis (FEA), which has become an effective method for femur biomechanical analysis, can exactly simulate intraoperative dislocation and fractures during THA.\textsuperscript{25,26}

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.

\textbf{Materials and Methods}

\textbf{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\textdegree, and a sharp angle of >45\textdegree; and (iv) local surgery history and the other with teratogenic disease.

\textbf{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
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 × 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.\(^\text{27}\) The cortical rate (CR) was calculated with Equation (1):

\[
CR = \frac{OD - ID}{OD}. \tag{1}
\]

**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 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 Hypermesh 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.
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 hexahedral 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 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 subdomains, 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). 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 ± 13.00 years for those in the normal group and the DDH group, and

| Table 1: The comparison of geometric parameters among three groups |
|---------------------------------------------------------------|
| Cortical bone cross-sectional area (mm²) | Cortical bone thickness (mm) |
| Group I model | 478 | 8 |
| Group II model | 478 × 0.7 | 8 |
| Group III model | 478 × 0.7 | 4.6 |

| 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 model   | 13,700        | 0.3                | 85,583          | 19,682          |
| Cancellous bone model | 840           | 0.3                | 13,426          | 58,381          |

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.
49.23 ± 12.08 years for those in the OP group. The body mass index (BMI) was 24.05 ± 2.39 kg/m² for participants in the normal and DDH groups, and 24.37 ± 2.45 kg/m² 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 in 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
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 \( (P < 0.00; \text{Fig. 5(B)}) \). 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):

| I      | II     | III    | I vs. II | z  | P-Value | I vs. III | z  | P-Value | II vs. III | 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 | -5.661 | 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.

**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 \( P < 0.001 \).
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. 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, and special anatomical structures change the otherwise homogeneous stress distribution of the healthy joint so that the stress concentration moves to the acetabular edge. 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. 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

![Table 4 The ID and OD of three simplified models](image)

| Model            | 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.

![Table 5 The comparison of Mises stress between theoretical results and FEA results](image)

| Model            | 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.
incidence of reduced bone stock and increased bone fragility,\textsuperscript{37,38} 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.

Acknowledgements

The authors wish to thank Prof. Ann for providing language modification to this article. We also thank Prof. Yusheng Qiu and Xiang Li for their expertise and kind help with the technique of FEA.

References

1. Learmonth ID, Young C, Rorabeck C. The operation of the century: total hip replacement. Lancet. 2007;370(9597):1508–19.
2. Kurtz S, Ong K, Lau E, Mowat F, Halpern M. Projections of primary and revision knee and hip arthroplasty in the United States from 2005 to 2030. J Bone Joint Surg Am. 2007;89(4):790–5.
3. Cottino U, Dettoni F, Caputo G, Bonasia DE, Rossi P, Rossi R. Incidence and pattern of periprosthetic hip fractures around the stem in different stem geometry. Int Orthop. 2020;44(1):53–9.
4. Tootik K, Lees L, Geilo B, Martinot P. Intraprocedural complications in total hip arthroplasty using a new cementless femoral implant (SP-CL®). J Orthop Traumatol. 2020;21(1):8.
5. Lunebourg A, Mousisin E, Cheris S, Ollivier M, Chevalley F, Wettstein M. Treatment of type B periprosthetic femur fractures with curved non-locating plate with eccentric holes: retrospective study of 43 patients with minimum 1-year follow-up. Orthop Traumatol Surg Res. 2015;101(3):277–82.
6. Colacchio ND, Robbins CE. Aghazadeh MS, Talmo CT, Bono JV. Total hip intraoperative femur fracture: do the design enhancements of a second-generation tapered-wedge stem reduce the incidence? J Arthroplasty. 2017;32(10):3163–8.
7. Huntzner JN, Hoppe DJ, Shapiro LM, Abrams GD, Safran M. Complication rates for hip arthroscopy are underestimated: a population-based study. Arthroscopy. 2017;33(6):1194–201.
8. Stange R, Raschke MJ, Fuchs T. Periprosthetic fractures. An interdisciplinary challenge. Unfallchirurg. 2011;114(6):688–98.
9. Katz JN, Wright EA, Polaris JJ, Harris MB, Losina E. Risk factors for periprosthetic fracture in older recipients of total hip replacement: a cohort study. BMC Musculoskelet Disord. 2014;15:168.
10. Lamb JN, Matharu GS, Redmond A, Judge A, West RM, Pandit HG. Risk factors for intraoperative periprosthetic femoral fractures during primary total hip arthroplasty. An analysis from the national joint registry for England and Wales and the Isle of Man. J Arthroplasty. 2019;34(12):3065–73.e1.
11. Haidukewych GJ, Jacofsky DJ, Hanssen AD, Lewallen DG. Intraoperative fractures of the acetabulum during primary total hip arthroplasty. J Bone Joint Surg Am. 2006;88(9):1952–60.
12. Learmonth ID, Morrisey DW, Hanley DA, Maksmynowycz WP, Bell NR, Juby AG, et al. Oral bisphosphonates are associated with reduced mortality after hip fracture. Osteoporos Int. 2011;22(3):983–91.
13. Beaufre LA, Morrisey DW, Hanley DA, Maksmynowycz WP, Bell NR, Juby AG, et al. Oral bisphosphonates are associated with reduced mortality after hip fracture. Osteoporos Int. 2011;22(3):983–91.
14. Ferguson RJ, Palmer AJ, Taylor A, Porter ML, Malchau H, Glyn-Jones S. Hip replacement. Lancet. 2018;392(10158):1662–73.
15. Della Rocca GJ, Leung KS, Pape HC. Periprosthetic fractures: epidemiology and future projections. J Orthop Trauma. 2011;25(Suppl 2):S66–70.
16. Hu K, Zhang X, Zhu J, Wang C, Ji W, Bai X. Periprosthetic fractures may be more likely in cementless femoral stems with sharp edges. J Orthop Sci. 2010;15(3):417–21.
17. Howie DW, Holubowycz OT, Middleton R. Large femoral heads decrease the incidence of dislocation after total hip arthroplasty: a randomized controlled trial. J Bone Joint Surg Am. 2012;94(12):1095–102.
18. Nie Y, Ning N, Pei F, Shen B, Zhou Z, L I G. Gait kinematic deviations in patients with developmental dysplasia of the hip treated with total hip arthroplasty. Orthopedics. 2017;40(3):e425–e31.
19. Huayamave V, Rose C, Serra S, Jones B, Divo E, Mosley F, et al. A patient-specific model of the biomechanics of hip reduction for neonatal developmental dysplasia of the hip: investigation of strategies for low to severe grades of developmental dysplasia of the hip. J Biomech. 2015;48(10):2026–33.
20. Benca E, Reisinger A, Patsch JM, Hirtler L, Synek A, Stenicka S, et al. Finite element analysis of mechanical behavior of human diaphyseal femur joints: a systematic review. Osteoarthr Cartil. 2017;25(4):438–47.
21. Huang L, Chen F, Wang S, Wei Y, Huang G, Chen J, et al. Three-dimensional finite element analysis of silk protein rod implantation after core decompression for osteonecrosis of the femoral head. BMC Musculoskelet Disord. 2019;20(1):544.
22. Husmann O, Rubin PJ, Leyvraz PF, de Roguin B, Argenson JN. Three-dimensional morphology of the proximal femur. J Arthroplasty. 1997;12(4):444–50.
28. Wickham H. ggplot2: Elegant Graphics for Data Analysis. Springer Verlag, New York, 2016.
29. Jewett BA, Collis DK. High complication rate with anterior total hip arthroplasties on a fracture table. Clin Orthop Relat Res. 2011;469(2): 503–7.
30. Zhang Z. Zhuo Q, Chai W, Ni M, Li H, Chen J. Clinical characteristics and risk factors of periprosthetic femoral fractures associated with hip arthroplasty: a retrospective study. Medicine. 2016;95(35):e4751.
31. Ricci WM. Periprosthetic femur fractures. J Orthop Trauma. 2015;29(3): 130–7.
32. Russell ME, Shivanna KH, Grosland NM, Pedersen DR. Cartilage contact pressure elevations in dysplastic hips: a chronic overload model. J Orthop Surg Res. 2006;1:6.
33. Chegini S, Beck M, Ferguson SJ. The effects of impingement and dysplasia on stress distributions in the hip joint during sitting and walking: a finite element analysis. J Orthop Res. 2009;27(2):195–201.
34. Henak CR, Abraham CL, Anderson AE, Maas SA, Ellis BJ, Peters CL, et al. Patient-specific analysis of cartilage and labrum mechanics in human hips with acetabular dysplasia. Osteoarthr Cartil. 2014;22(2):210–7.
35. Endo D, Ogami-Takamura K, Imamura T, Saiki K, Mural K, Okamoto K, et al. Reduced cortical bone thickness increases stress and strain in the female femoral diaphysis analyzed by a CT-based finite element method: implications for the anatomical background of fatigue fracture of the femur. Bone Reports. 2020; 13:100733.
36. Power J, Loveridge N, Kröger H, Parker M, Reeve J. Femoral neck cortical bone in female and male hip fracture cases: differential contrasts in cortical width and sub-periosteal porosity in 112 cases and controls. Bone. 2018;114:81–9.
37. Ensrud KE, Crandall CJ. Osteoporosis. Ann Intern Med. 2017;167(3): Iic17–32.
38. Hoppe S, Uhlmann M, Schwin R, Suhm N, Benneker LM. Intraoperative mechanical measurement of bone quality with the DensiProbe. J Clin Densitom. 2015;18(1):109–16.