Arthroplasty Today 14 (2022) 105–109

Contents lists available at ScienceDirect

Arthroplasty Today

journal homepage: http://www.arthroplastytoday.org/

Original research

Finite Element Analysis of Optimal Positioning of Femoral Osteotomy in Total Hip Arthroplasty With Subtrochanteric Shortening

Daisuke Takahashi, MD, PhD [a, *], Yoshihiro Noyama, PhD [b], Tomohiro Shimizu, MD, PhD [a], Mohamad Alaa Terkawi, DVM, PhD [a], Norimasa Iwasaki, MD, PhD [a]

[a] *Department of Orthopaedic Surgery, Faculty of Medicine and Graduate School of Medicine, Hokkaido University, Sapporo, Japan*
[b] *Department of Pharmaceutical Affairs Division, Teijin Nakashima Medical Company Limited, Okayama, Japan*

ARTICLE INFO

Article history:
Received 11 October 2021
Received in revised form
22 December 2021
Accepted 15 January 2022
Available online xxx

Keywords:
Total hip arthroplasty
Finite element analysis
Femoral shortening

ABSTRACT

Background: Total hip arthroplasty with femoral shortening is frequently recommended for patients with high hip dislocation. However, the possibility of postoperative rotational deviation of the stem presents a challenge for surgeons. We aimed to determine the optimal position for osteotomy in total hip arthroplasty under full weight-bearing and turning torque by using finite element analysis.
Methods: Four models of femoral osteotomy with 30-mm transverse shortening at 30% (model 30), 40% (model 40), 50% (model 50), and 60% (model 60) from the proximal end of the full length of the Exeter stem were constructed. Using finite element analysis, the constructs were first analyzed under an axial load of 1500 N and then with an added torsional load of 10°.
Results: The analyses under torsional loading conditions revealed that the maximum von Mises stress on the stem in each model occurred at the proximal end of the distal fragment and the distal side of the stem. The maximum stress values at the stem were 819 MPa (model 30), 825 MPa (model 40), 916 MPa (model 50), and 944 MPa (model 60). The maximum stress values at the osteotomy site of the medullary cavity side of the distal bone fragment were 761 MPa (model 30), 165 MPa (model 40), 187 MPa (model 50), and 414 MPa (model 60).
Conclusions: The osteotomy level should be around the proximal 40% of the full length of the Exeter stem, which is most suitable for rotation stability in the early postoperative period.

Introduction

Total hip arthroplasty (THA) is a surgical procedure for hip joint replacement with an artificial prosthesis that has been proven to improve the quality of life for most patients with hip disorders such as osteoarthritis [1]. However, THA for Crowe type IV developmental dysplasia of the hip (DDH) is technically demanding and presents many problems for the hip surgeon. Restoration of the hip center to the true acetabulum in THA for Crowe type IV DDH may lengthen the leg excessively and cause nerve palsy. Therefore, THA with femoral shortening is the most recommended surgical approach to reduce the risk of nerve palsy in patients with high hip dislocation due to DDH [2,3]. Previous reports have demonstrated various subtrochanteric osteotomy techniques with many cutting shapes, including transverse, oblique, Z-shaped, and double-chevron [4-10]. Transverse osteotomy may be recommended because of the minimal invasion of the periosteum at the osteotomy site and the relative technical ease of cutting and adjusting the anteversion angle [11]. This procedure has been broadly performed with a cemented stem and has shown good clinical results [12]. However, the possibility of rotational deviation of the stem in the early postoperative period presents a challenge for surgeons. Although one report determined the optimal osteotomy position by evaluating the contact area and coincidence rate between the proximal and distal fragments [13], no previous study has demonstrated the mechanical effects on the stem and bone. Because femoral osteotomy positioning is an important factor influencing the rotational deviation, the aim of the present study was to use finite element analysis (FEA) to determine the optimal

---

* Corresponding author. Kita-15, Nishi-7, Kita-ku, Sapporo, Japan. Tel.: +81 11 706 5935.
E-mail address: rainbow-quest@pop02.odn.ne.jp

https://doi.org/10.1016/j.artd.2022.01.021

position for osteotomy in THA with an Exeter cemented stem under conditions of full weight-bearing and turning torque.

Material and methods

Construction of the FEA model

A 3D model of composite femurs (4th generation; Sawbones Worldwide, Vashon, WA) was constructed using computed tomography imaging analysis (Mimics 16, Materialize; Software & Services for Biomedical Engineering, Leuven, Belgium) with data obtained from X-ray computed tomography (Eclos-4S; Hitachi, Otawara, Tochigi, Japan) [14]. THA with the femoral shortening model was assembled in a 3D-computer-aided design software (UG NX 5; SIEMENS, Plano, TX). Four models were constructed with femoral osteotomy at 30% (model 30), 40% (model 40), 50% (model 50), and 60% (model 60) from the proximal region of the full length of the Exeter femoral cemented stem (Stryker, Kalamazoo, MI). Segmental resection was performed in each group to create a 30-mm transverse shortening (Fig. 1).

Material properties

All sections were assigned isotropic material properties with an elastic modulus of 16.7 GPa for cortical bone [15], 0.155 GPa for cancellous bone [16], 2.8 GPa for polymethylmethacrylate cement [17], 195 GPa for Orthinox stainless steel (Stryker, Kalamazoo, MI) [18], and 210 GPa for Co-Cr [19]. A Poisson's ratio of 0.3 was used for all materials [18].

FEA modeling

A finite element preprocessor was generated using HyperMesh 14 (Altair Engineering, Troy, MI). Tetrahedral primary elements were used, and the numbers of elements and nodes were 841,875 and 182,701 in the composite femurs before cutting, respectively. To set up the boundary conditions, the cortical bone-trabecular bone, cortical bone-cement, and trabecular bone-cement were fixed by glue, with coefficients of friction of 0.1, 0.25, and 0.8 at the proximal cortical bone-distal cortical bone, stem-cement, and stem-femoral head interfaces, respectively [20]. The distal end of the femoral model was fixed with the cement. These constructs were positioned at 15° adduction in the frontal plane and aligned vertically in the sagittal plane (Fig. 1). This position was used to simulate the anatomical one-legged stance. Next, the constructs were tested under (1) an axial load of 1500 N alone and (2) an axial load of 1500 N with a torsional load of 10°, and the results were then analyzed using a nonlinear FEA software program (M.S.C. Marc 2017; MSC Software, Newport Beach, CA) (Fig. 2).

Data analysis and statistics

Statistical analysis was performed using Student's t-test to compare the differences between two independent groups, and the results were considered significant when $P < .05$. Data are presented as the mean ± standard error of the mean (SEM). All statistical analyses were performed using SPSS Statistics (Version 23.0; IBM Corporation, Armonk, NY).

Results

To define areas of high stress and stress shielding with femoral osteotomy in cemented THA with subtrochanteric shortening models, the von Mises stress distributions with an axial load of 1500 N alone and with an additional torsional load of 10° were determined by FEA. In our analysis under only axial load conditions, the maximum stress values at the neck and middle level of the stem were less than 90 MPa in each model (Fig. 3). Under both axial and torsional loading, the maximum von Mises stress on the stem in each model occurred at the proximal end of the distal bone fragment and the distal side of the stem. The maximum stress values at the stem were 591 MPa (model 30), 543 MPa (model 40), 609 MPa (model 50), and 640 MPa (model 60) (Fig. 4). On the other hand, the maximum stress values at the osteotomy site of the medullary cavity side of the distal bone fragment were 496 MPa (model 30), 77 MPa (model 40), 77 MPa (model 50), and 265 MPa (model 60) (Fig. 5).

Discussion

THA with femoral shortening is the most frequently recommended surgical approach for the treatment of Crowe type IV DDH [2,3]. Polished tapered cemented stems have been broadly used in this procedure and have shown good clinical results [12]. Transverse osteotomy is ideal in THA with femoral shortening because it

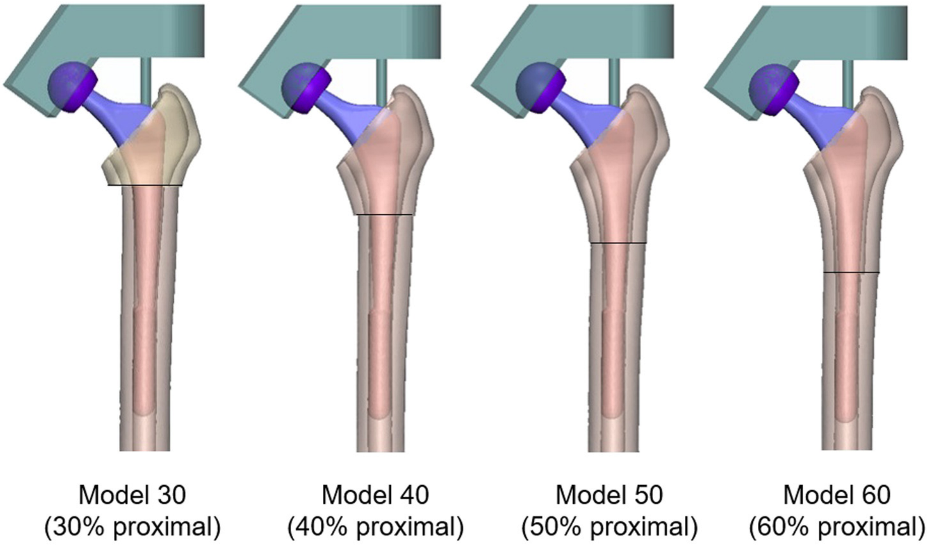

Figure 1. A three-dimensional model of four different methods for finite element analysis of optimal positioning of femoral osteotomy in total hip arthroplasty with subtrochanteric shortening.

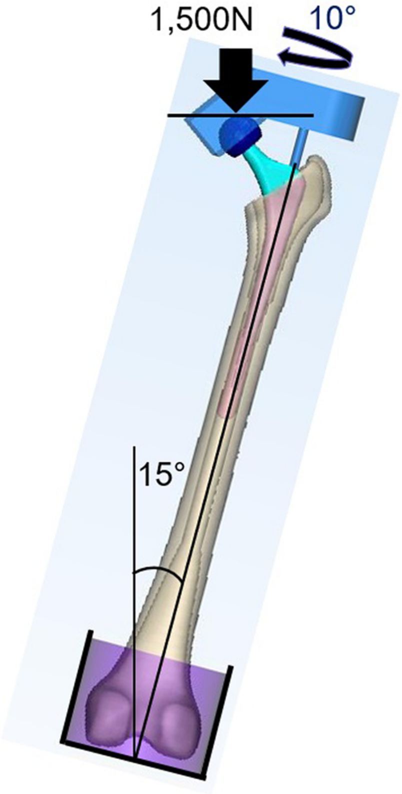

Figure 2. Conditions for finite element analysis of optimal positioning of femoral osteotomy in total hip arthroplasty with subtrochanteric shortening. The constructs are positioned at 15° adduction in the frontal plane and aligned vertically in the sagittal plane. Four different models were analyzed under an axial load of 1500 N and a torsional loading of 10°.

is easy to adjust to an appropriate rotation angle [11]. On the other hand, the possibility of nonunion due to rotational deviation of the stem in the early postoperative period is a problem for surgeons. The incidence of nonunion at the osteotomy site ranges from 0% to 22%, regardless of the type of osteotomy [21-26]. Reikeraas et al. [27] analyzed 25 dislocated hips treated with subtrochanteric transverse osteotomy and found delayed union in 4% and malunion in 4% of the cases [27]. Yasgur et al. reported one case of nonunion in a series of eight cases [28], and Masonis et al. reported that 2 of 21 hips required revision surgery because of nonunion at the subtrochanteric transverse osteotomy site [6]. In contrast, Kawai et al. showed that bone union was obtained at the osteotomy sites in all cases [29]. However, no study has demonstrated the mechanical effect on the stem and bone under the condition of transverse osteotomy in THA with femoral shortening. Considering the importance of femoral osteotomy positioning as an important factor influencing the rotational deviation, the aim of the present study was to determine the optimal position for osteotomy in THA with an Exeter cemented stem under conditions of full weight-bearing and turning torque by using FEA.

The results of the present study showed that the stress areas were present at the distal side of the stem under the axial and torsional loading conditions in each model, and the maximum stress values were lower in the construct with osteotomy at a position of 40% proximal (model 40). The maximum stress values in the constructs with osteotomy at positions of 50% and 60% were over 600 MPa, which were close to the maximum stress value of stainless steel (ca. 800 MPa) [30]. Next, the maximum stress values at the osteotomy site at the medullary cavity side of the proximal end of the distal bone fragment for models 40 and 50 were the lowest in all groups. These results show that model 40 has the least stress concentration and minimized the risk of postoperative deviation in examinations of both stem and femur components.

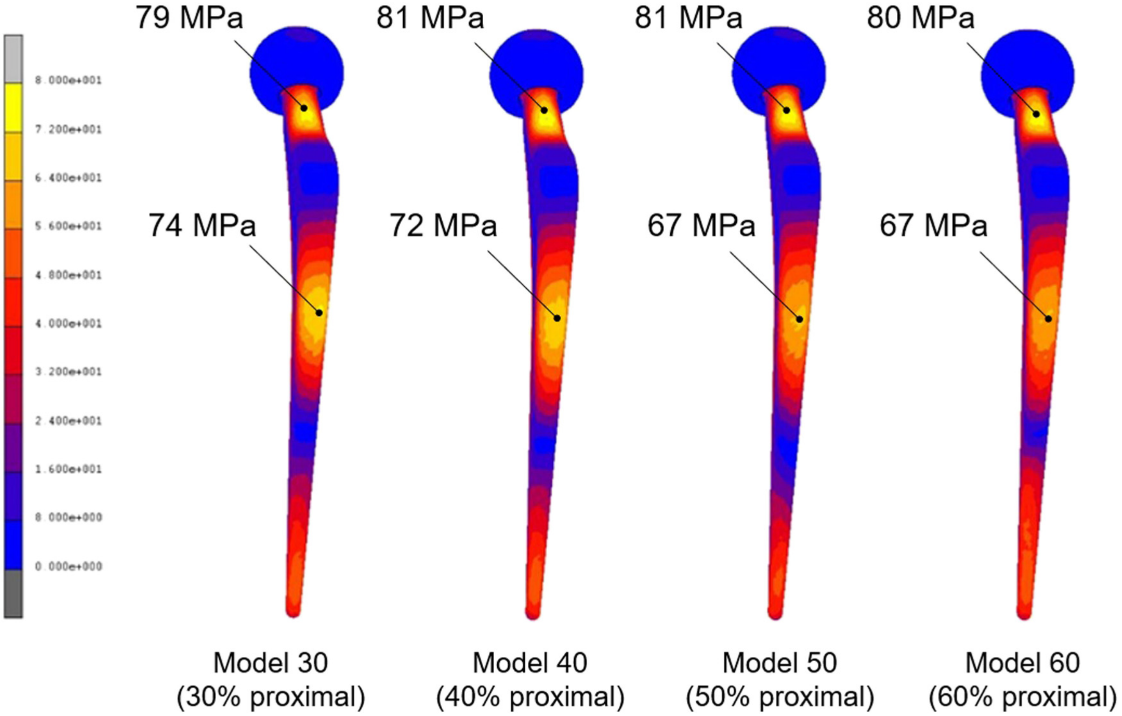

Figure 3. Findings of finite element analysis for the pattern of von Mises stress distributions at the stem side in four different models under 1500-N axial loading.

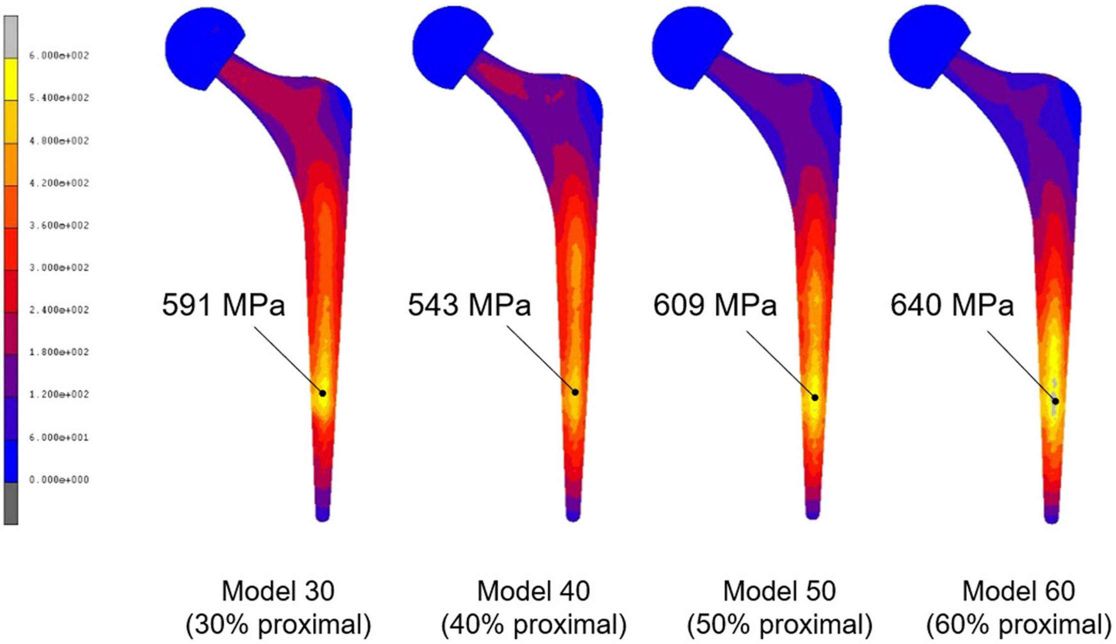

Figure 4. Findings of finite element analysis for the pattern of von Mises stress distributions at the stem side in four different models under 1500-N axial loading and 10° torsional loading. Comparison of the maximum stress at the stem side.

Kawai et al. suggested that the femoral stem should pass from at least 7 cm from the osteotomy site to obtain bone union [29]. Ozan et al. believed that the femoral stem should bridge the osteotomy site by at least 4-5 cm [31], but they noted fibrous union in one patient and varus angulation deformity of the femoral stem in another patient at the end of follow-up. Our results suggest that the Exeter cemented stem should pass from the osteotomy site for approximately 9 cm to achieve an appropriate strain value. On the other hand, Huang et al. determined the optimal osteotomy position by evaluating the contact area and coincidence rate between the proximal and distal fragments [13] and demonstrated that a level 1 cm below the lesser trochanter was optimal. Their conclusions support the findings of the present study.

The limitations of this study are as follows: (1) Because the axial loading and rotation angle values in this study were based on the findings of previous reports, they do not necessarily reflect actual clinical settings. However, model 40 was the most suitable osteotomy model under all other conditions. (2) In our study, static loads were analyzed by a geometrically nonlinear analysis, but not perturbation analysis, because perturbation analysis is specifically performed for evaluating the simulation at an initial stage, and patients with THA with osteotomy are not expected to perform intense exercise immediately after surgery.

To our knowledge, this is the first study reporting FEA of torsional loading for THA with femoral shortening by using a polished tapered cemented stem. The present results showed that the

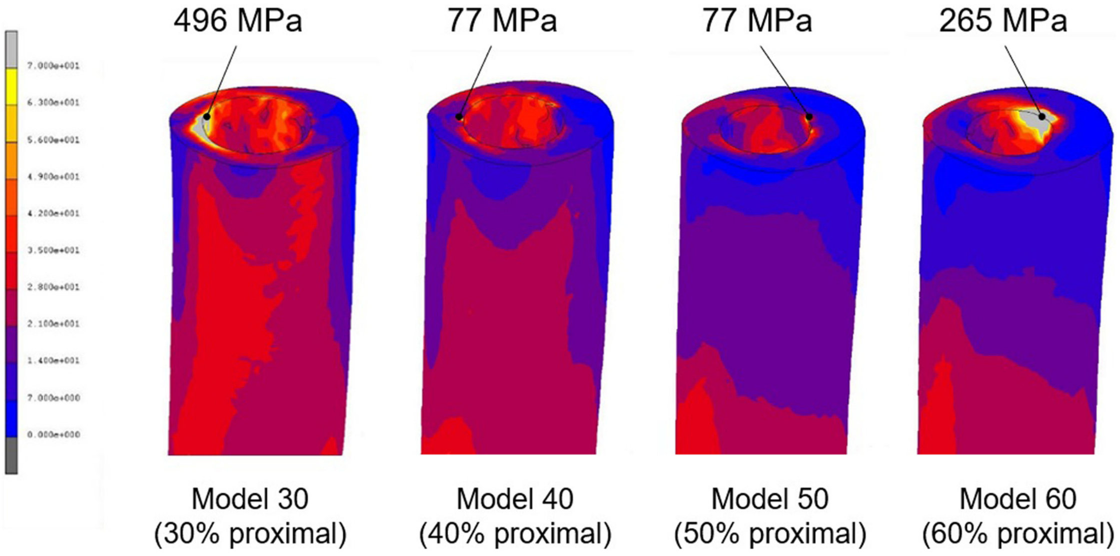

Figure 5. Findings of finite element analysis for the pattern of von Mises stress distributions at the distal fragment of the femur in four different models under 1500-N axial loading and 10° torsional loading. Comparison of the maximum stress at the proximal end of the distal fragment.

osteotomy level should be around the proximal 40% of the full length of the Exeter stem and that this approach was the most suitable for maintenance of rotation stability in the early postoperative period.

Conclusion

Our results showed that the stress areas were present at the distal side of the stem, and the maximum stress value was the lowest in the construct with osteotomy at the 40% position under the torsional loading condition. The maximum stress values in the constructs with osteotomy at positions of 50% and 60% were close to the yield stress of stainless steel at 800 MPa, indicating a high risk of stem breakage. The present results showed that the osteotomy level should be around the proximal 40% of the full length of the Exeter stem, which is most suitable for avoiding the rotation displacement that may occur in the early postoperative period.

Acknowledgment

The authors would like to thank Editage (www.editage.com) for English language editing.

Conflicts of interest

The authors declare there are no conflicts of interest.

For full disclosure statements refer to https://doi.org/10.1016/j.artd.2022.01.021

References

[1] Halawi MJ. Outcome measures in Total joint arthroplasty: current status, challenges, and future directions. Orthopedics 2015;38:e685.

[2] Krych AJ, Howard JL, Trousdale RT, Cabanela ME, Berry DJ. Total hip arthroplasty with shortening subtrochanteric osteotomy in Crowe type-IV developmental dysplasia: surgical technique. J Bone Joint Surg Am 2010;92(Suppl. 1 Pt 2):176.

[3] Kiliçoğlu Oİ, Türker M, Akgül T, Yazicioğlu O. Cementless total hip arthroplasty with modified oblique femoral shortening osteotomy in Crowe type IV congenital hip dislocation. J Arthroplasty 2013;28:117.

[4] Togrul E, Ozkan C, Kalaci A, Gülşen M. A new technique of subtrochanteric shortening in total hip replacement for Crowe type 3 to 4 dysplasia of the hip. J Arthroplasty 2010;25:465.

[5] Hua WB, Yang SH, Xu WH, et al. Total hip arthroplasty with subtrochanteric femoral shortening osteotomy for high hip dislocation. Orthop Surg 2015;7:112.

[6] Masonis JL, Patel JV, Miu A, et al. Subtrochanteric shortening and derotational osteotomy in primary total hip arthroplasty for patients with severe hip dysplasia: 5-year follow-up. J Arthroplasty 2003;18(Suppl. 1):68.

[7] Koulouvaris P, Stafylas K, Sculco T, Xenakis T. Distal femoral shortening in total hip arthroplasty for complex primary hip reconstruction. A new surgical technique. J Arthroplasty 2008;23:992.

[8] Paavilainen T. Total hip replacement for developmental dysplasia of the hip. Acta Orthop Scand 1997;68:77.

[9] Thorup B, Mechlenburg I, Søballe K. Total hip replacement in the congenitally dislocated hip using the Paavilainen technique: 19 hips followed for 1.5–10 years. Acta Orthop 2009;80:259.

[10] Hasegawa Y, Iwase T, Kanoh T, Seki T, Matsuoka A. Total hip arthroplasty for Crowe type IV developmental dysplasia. J Arthroplasty 2012;27:1629.

[11] Ogawa H, Ito Y, Shinozaki M, Matsumoto K, Shimizu K. Subtrochanteric transverse shortening osteotomy in cementless total hip arthroplasty achieved using a modular stem. Orthopedics 2011;34:170.

[12] Charity JA, Tsiridis E, Sheeraz A, et al. Treatment of Crowe IV high hip dysplasia with total hip replacement using the Exeter stem and shortening derotational subtrochanteric osteotomy. J Bone Joint Surg Br 2011;93:34.

[13] Huang ZY, Liu H, Li M, Ling J, Zhang JH, Zeng ZM. Optimal location of subtrochanteric osteotomy in total hip arthroplasty for crowe type IV developmental dysplasia of hip. B.M.C Musculoskelet Disord 2020;21:210.

[14] Noyama Y, Nakano T, Ishimoto T, Sakai T, Yoshikawa H. Design and optimization of the oriented groove on the hip implant surface to promote bone microstructure integrity. Bone 2013;52:659.

[15] Heiner AD. Structural properties of fourth-generation composite femurs and tibias. J Biomech 2008;41:3282.

[16] Shah S, Kim SY, Dubov A, Schemitsch EH, Bougherara H, Zdero R. The biomechanics of plate fixation of periprosthetic femoral fractures near the tip of a total hip implant: cables, screws, or both? Proc Inst Mech Eng H 2011;225:845.

[17] Harrigan TP, Kareh JA, O'Connor DO, Burke DW, Harris WH. A finite element study of the initiation of failure of fixation in cemented femoral total hip components. J Orthop Res 1992;10:134.

[18] Chen G, Schmutz B, Wullschleger M, Pearcy MJ, Schuetz MA. Computational investigations of mechanical failures of internal plate fixation. Proc Inst Mech Eng H 2010;224:119.

[19] Katti KS. Biomaterials in total joint replacement. Colloids Surf B Biointerfaces 2004;39:133.

[20] Viceconti M, Muccini R, Bernakiewicz M, Baleani M, Cristofolini L. Large-sliding contact elements accurately predict levels of bone-implant micromotion relevant to osseointegration. J Biomech 2000;33:1611.

[21] Rollo G, Solarino G, Vicenti G, Picca G, Carrozzo M, Moretti B. Subtrochanteric femoral shortening osteotomy combined with cementless total hip replacement for Crowe type IV developmental dysplasia: a retrospective study. J Orthop Traumatol 2017;18:407.

[22] Park MS, Kim KH, Jeong WC. Transverse subtrochanteric shortening osteotomy in primary total hip arthroplasty for patients with severe hip developmental dysplasia. J Arthroplasty 2007;22:1031.

[23] Biant LC, Bruce WJ, Assini JB, Walker PM, Walsh WR. Primary total hip arthroplasty in severe developmental dysplasia of the hip. Ten-year results using a cementless modular stem. J Arthroplasty 2009;24:27.

[24] Bruce WJ, Rizkallah SM, Kwon YM, Goldberg JA, Walsh WR. A new technique of subtrochanteric shortening in total hip arthroplasty: surgical technique and results of 9 cases. J Arthroplasty 2000;15:617.

[25] Wang D, Li DH, Li Q, et al. Subtrochanteric shortening osteotomy during cementless total hip arthroplasty in young patients with severe developmental dysplasia of the hip. BMC Musculoskelet Disord 2017;18:491.

[26] Li C, Zhang C, Zhang M, Ding Y. Comparison of transverse and modified subtrochanteric femoral shortening osteotomy in total hip arthroplasty for developmental dysplasia of hip: a meta-analysis. BMC Musculoskelet Disord 2014;15:331.

[27] Reikeraas O, Lereim P, Gabor I, Gunderson R, Bjerkreim I. Femoral shortening in total arthroplasty for completely dislocated hips: 3–7 years results in 25 cases. Acta Orthop Scand 1996;67:33.

[28] Yasgur DJ, Stuchin SA, Adler EM, DiCesare PE. Subtrochanteric femoral shortening osteotomy in total hip arthroplasty forhigh-riding developmental dislocation of the hip. J Arthroplasty 1997;12:880.

[29] Kawai T, Tanaka C, Ikenaga M, Kanoe H. Cemented total hip arthroplasty with transverse subtrochanteric shortening osteotomy for Crowe group IV dislocated hip. J Arthroplasty 2011;26:229.

[30] Brunski JB. Metals. In: Ratner BD, et al., editors. Classes of materials used in Medicine. Biomaterials Science: an introduction to material in Medicine. 2nd ed. CA: Elsevier Academic Press; 2004. p. 137.

[31] Ozan F, Uzun E, Gürbüz K, Koyuncu Ş Altay T, Kayalı C. Total hip arthroplasty in the developmental dysplasia of the hip using transverse subtrochanteric osteotomy. J Orthop 2016;13:259.