Article published online: 2021-12-13

THIEME OPEN ACCESS

Strain Analysis in Cementless Hip Femoral Prosthesis using the Finite Element Method – Influence of the Variability of the Angular Positioning of the Implant*

Análise da deformação na prótese femoral não cimentada do quadril pelo método de elementos finitos – Influência da variabilidade do posicionamento angular do implante

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Rev Bras Ortop 2022;57(6):968–974.

Abstract

Objective The present study aims to evaluate the influence of different positioning of the hip femoral prosthesis on the stress and strain over this implant.

Methods A femoral prosthesis (Taper - Víncula, Rio Claro, SP, Brazil) was submitted to a stress and strain analysis using the finite element method (FEM) according to the *International Organization for Standardization (ISO) 7206-6 Implants for surgery – Partial and total hip joint prostheses – Part 6: Endurance properties testing and performance requirements of neck region of stemmed femoral components* standard. The analysis proposed a branch of the physical test with a +/− 5° angle variation on the standard proposed for α and β variables.

Results The isolated +/− 5° variation on the α angle, as well as the association of +/− 5° variation on the α and β angles, presented significant statistical differences compared with the control strain ($p = 0.027$ and 0.021, respectively). Variation on angle β alone did not result in a significant change in the strain of the prosthesis ($p = 0.128$). The stem positioning with greatest implant strain was α = 5° and β = 14° ($p = 0.032$).

Keywords
- arthroplasty, replacement, hip
- hip prosthesis
- finite element analysis
- equipment failure analysis

* Study developed at Escola Paulista de Medicina, Universidade Federal de São Paulo, São Paulo, SP, Brazil.

received January 12, 2021
accepted April 12, 2021
published online December 13, 2021

DOI https://doi.org/10.1055/s-0041-1735141.
ISSN 0102-3616.

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Conclusion A variation on the positioning of the prosthetic femoral stem by +/− 5° in the coronal plane and/or the association of a +/− 5° angle in coronal and sagittal planes significantly influenced implant strain.

Resumo

Objetivo Avaliar a influência da variação do posicionamento da prótese femoral do quadril na tensão e na deformação produzidas neste implante.

Métodos Utilizou-se a análise de tensão e de deformação da prótese femoral (Taper, Víncula, Rio Claro, SP, Brasil) pelo método de elementos finitos (MEF) de acordo com a norma *ISO 7206-6 Implants for surgery - Partial and total hip joint prostheses–Part 6: Endurance properties testing and performance requirements of neck region of stemmed femoral components.* A análise propôs uma ramificação do ensaio físico, com variação da angulação de +/− 5° sobre a proposta normativa das variáveis α e β.

Resultados Ao comparar com a deformação controle, houve significância estatística com a angulação isolada de +/− 5° do ângulo α, bem como com a associação de +/− 5° nas angulações α e β ($p = 0,027$ e 0,021, respectivamente). Já com a variação apenas do ângulo β, não houve variação significativa na deformação da prótese ($p = 0,128$). A posição da haste com maior deformação no implante foi com α = 5° e β = 14° ($p = 0,032$).

Conclusão A variabilidade de posicionamento da haste femoral protética de +/− 5° no plano coronal e/ou a associação da angulação de +/− 5° nos planos coronal e sagital interferiu de forma significativa na deformação do implante.

Palavras-chave
- artroplastia de quadril
- prótese de quadril
- análise de elementos finitos
- análise de falha de equipamento

Introduction

Total hip arthroplasty (THA) is one of the most successful surgeries today, with excellent long-term outcomes. However, the success of the procedure depends on several factors, including correct surgical indication, adequate planning, and effective surgical technique.[1]

The cyclic load imposed on the hip during a wide range of activities is extremely high.[2] The prosthetic joint must be prepared to withstand such stress loads, resisting the imposed strain. The orthopedic surgeon must reconstruct the hip biomechanics in the most suitable way at arthroplasty, restoring muscle strength momentum to ensure a long-term survival of the implant. The correct positioning of the prosthetic components is critical to the harmonic transfer of loads over the hip and good mechanical joint functioning.[3]

Experimentally, preclinical laboratory biomechanical tests determine the fatigue strength properties of a prosthetic femoral stem; these tests include those recommended by the International Organization for Standardization (ISO) 7206-4 and ISO 7206-6 standards (►**Figure 1**).[4,5] Material strength is evaluated by the stress-strain curve. In conventional tests, the load is increased until the material breaks. Using the finite element method (FEM), a computer simulation of the implant's behavior against cyclic loads is performed based on simplified biomechanical tests and previously known physical-chemical properties of the material. The FEM decreases the execution time and cost compared to traditional biomechanical simulations.[6]

Usual biomechanical tests for femoral stems recommend the progressive increase of cyclic loads with the femoral component in a fixed angular position.[7,8] Thus, these tests neglect the behavior of femoral stems implanted in varus/valgus or anticurve/recurve, which are commonly seen in clinical practice and potentially have a decisive influence on the long-term survival of the implant. Thus, the objective of the present study is to evaluate, using FEM, the influence of the variability of the angular positioning of a prosthetic femoral stem on the stress and strain over the implant.

Material and Methods

First, a laboratory biomechanical test of the prosthetic femoral stem (Taper - Víncula, Rio Claro, SP, Brazil) was performed (►**Figure 2**) in a fixed angular position according to the ISO 7206-4 (►**Figure 1**) and ISO 7206-6 standards.[4,5] This anatomically designed, triple-wedge titanium stem presents a cementless fixation method and proximal porosities for osteointegration.

This study was based on data from the initial biomechanical test and the physicochemical properties of the prosthesis. At the Ansys Workbench 19.1 platform, an online virtual engineering portal (ANSYS, Inc. Canonsburg, PA, USA), the platform's "solver static structural" was used along with the parameterization of load vector components. This additional analysis proposed a branch of the physical test with +/− 5° angular variations in the coronal and sagittal planes in relation to the angle recommended by ISO.

The material's characteristics inserted in the platform were provided by the *ASTM F136–Standard Specification for Wrought Titanium-6Aluminum-4Vanadium ELI (Extra Low Interstitial) Alloy for Surgical Implant Applications (ASTM F136, 2013)* standard[9] (►**Table 1**). Although the modulus of elasticity of this material is approximately 110 Gpa, its shear

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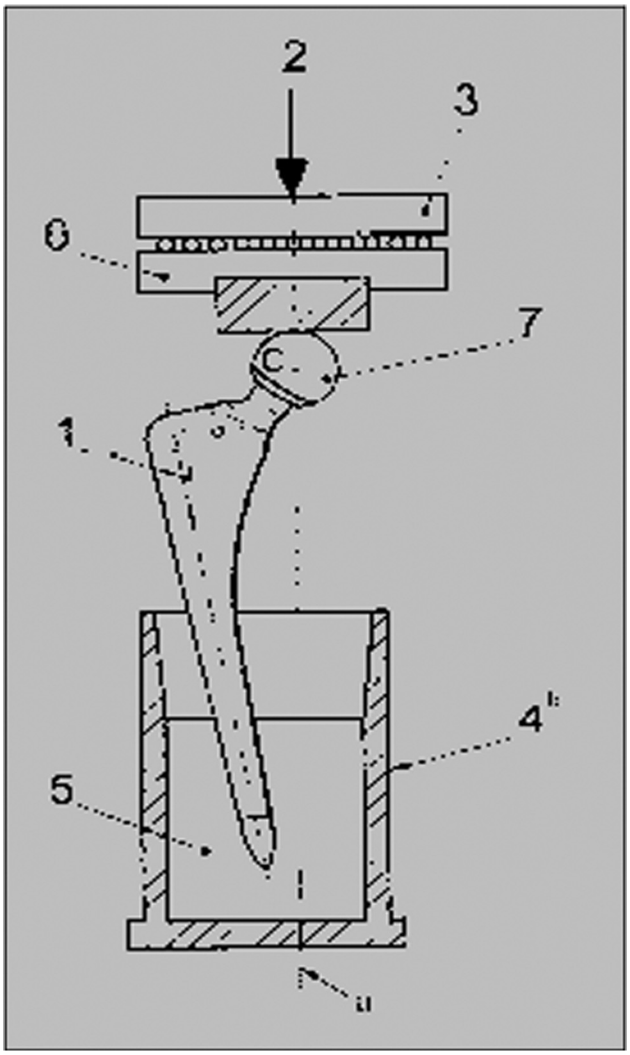

Fig. 1 ISO 7206–4 mechanical test.
Source: Image from ISO 7206–4, 2010.

Fig. 2 Geometric representation.
Source: Author's collection.

strength is relatively low. Physical properties of the titanium alloy include a tensile strength of 780 to 1,050 GPa, density of 4.4 g/cm^3, and a Poisson ratio of 0.34.[10] For the purposes of computational analysis, the behavior of the material under loads was considered perfectly plastic (►**Figure 3**).

Boundary Conditions (Loading and Movement Restrictions)

The test was carried out per ISO 7206–6,[5] but with a movement restriction on the prosthesis during load application, a condition known as "bonded" (►**Figure 4**). To eliminate tension concentrators in the region of main interest for the study (the neck-body transition), the setting was made 10 mm below the point proposed by the technical standard. For loading, a vector was applied to the cone, where coupling with the femoral head is usually performed, simulating the center of rotation of the system (►**Figure 4**).

Table 1 Material properties

Properties	Alloy (F136)
Breaking stress [MPa]	860
Yield [MPa]	795
Elongation [%]	10
Area reduction [%]	20

Source: Table adapted from Park & Lakes, 2007.

Load components variation was calculated by load vector decomposition (►**Figure 5**). The standard positioning of the femoral stem according to the aforementioned technical standard was α angle = 10° and β angle = 9°, with an applied force of 5,340 N. Subsequent computational tests were performed with the same force applied in different combinations of +/– 5° α and β angles, as shown in ►**Table 2**.

Finite Element Model (Mesh)

The mesh for system interpretation was based on a parabolic solid tetrahedral element with an average size of 3 mm filling the prosthesis body region. The cone-neck block used a dominant hexahedral element with an average size of 2 mm (►**Figure 6**).

The stem area for the stress versus strain test was chosen based on the equivalent stress in six different regions of the prosthesis. The area with the highest equivalent stress (neck-

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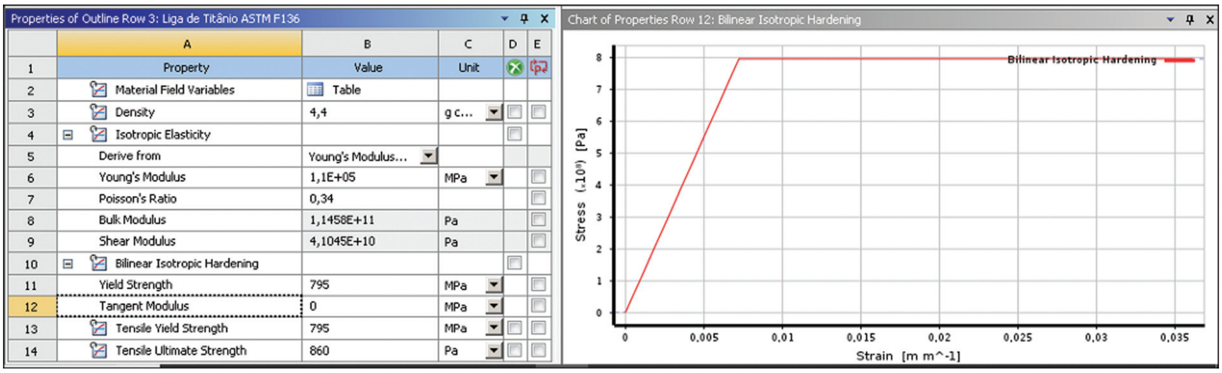

Fig. 3 Material properties.
Source: Author's collection.

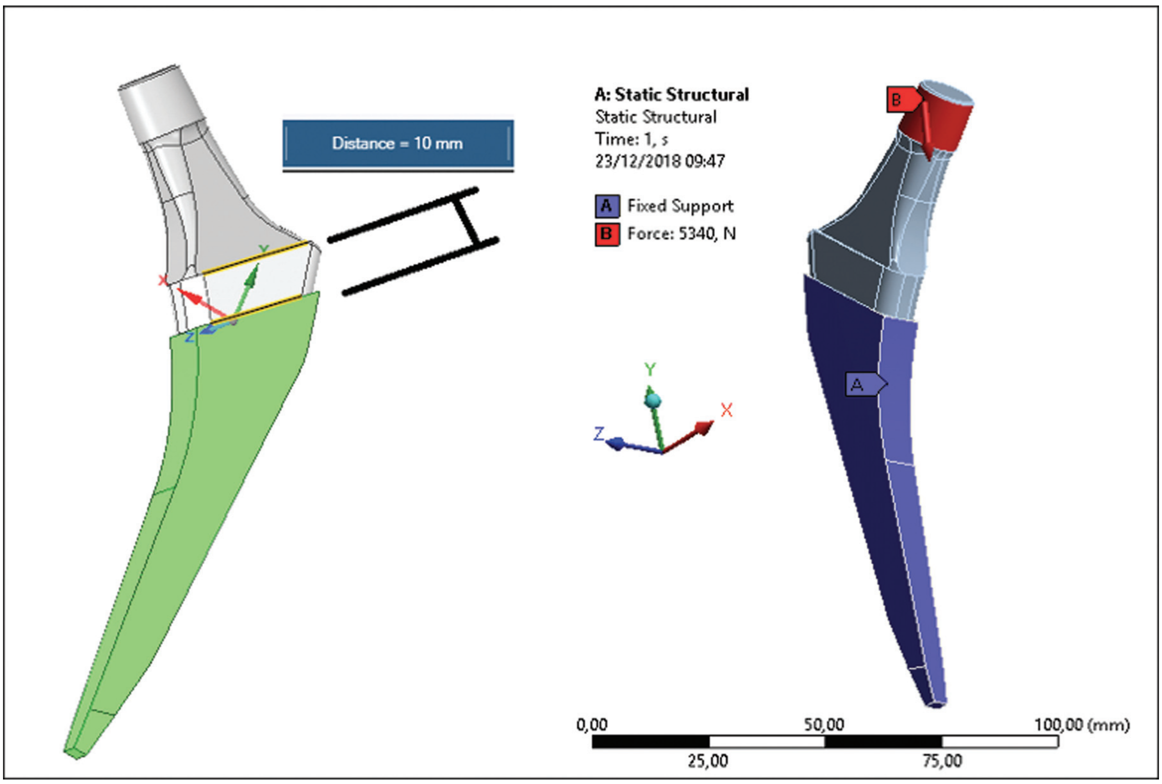

Fig. 4 Boundary conditions.
Source: Author's collection.

body transition–stem introducer coupling point) was chosen, as demonstrated in ► **Table 3** and ► **Figure 7**.

Statistical Analysis

The statistical analysis was performed with the Excel Office 2010 software (Microsoft Corp., Redmond, WA, USA) and the IBM SPSS Statistics for Windows, Version 20.0 (IBM Corp., Armonk, NY, USA). Variables were compared using the Student t-test after checking data normality and variance. Significance was set as *p*-value equal to 0.05 and a 95% confidence interval.

Results

► **Table 4** describes stress and strain findings in the neck-body transition region of the stem in different positions.

The statistical analysis was separated into three scenarios:

1) Comparison of the test strain in standard position ($\alpha = 10°$ and $\beta = 9°$) with α angle variation (5° and 15°) alone
2) Comparison of the test strain in standard position ($\alpha = 10°$ and $\beta = 9°$) with β angle variation (4° and 14°) alone
3) Comparison of the test strain in standard position with α and β angles variation (α, 5° and 15°; β, 4° and 14°)

Scenarios 1 and 3 presented significant statistical difference ($p = 0.027$ and 0.021, respectively). There was no significant variation in prosthesis strain with different β angles alone ($p = 0.128$).

The stem position with greatest implant strain was $\alpha = 5°$ and $\beta = 14°$ ($p = 0.032$).

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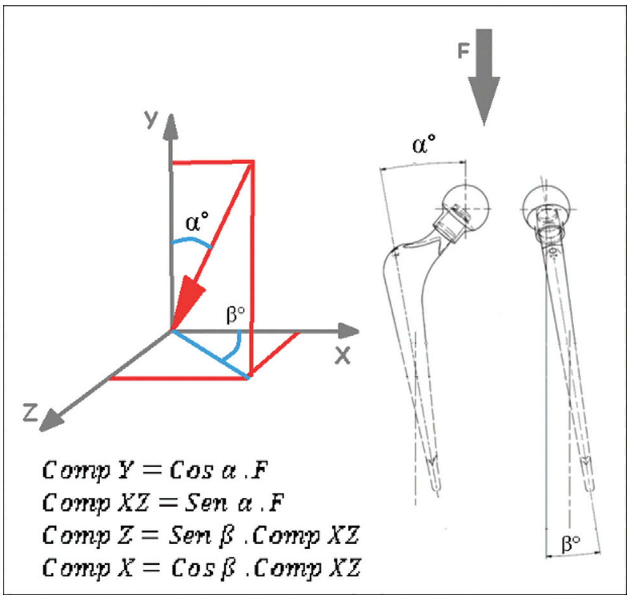

Fig. 5 Force components.
Source: Author's collection.

None of the tested mechanical stresses caused the material to fail, as the response values did not exceed the flow values.

Discussion

In an unprecedented way, the current study evaluated the effect of varying the femoral component positioning on the strain over the implant using FEM. The main findings were that a +/− 5° variation in the coronal plane or in the coronal and sagittal plane of the femoral prosthesis in a computational test using FEM resulted in a significant increase in the strain over the implant.

In 2016, Goel and Nyman[11] cited the potential of using FEM to analyze the biomechanics of human joints. In 2019, Akrami et al.[12] described the use of FEM to analyze hip biomechanics in a study based on magnetic resonance images from a 20-year-old volunteer with no joint injuries. This study demonstrated the mechanical properties of

Table 2 Load angulation range

α°	β°	Comp X [N]	Comp Y [N]	Comp Z [N]
10	9	915.86	5,258.87	145.06
10	4	925.02	5,258.87	64.68
10	14	899.74	5,258.87	224.33
5	9	459.68	5,319.68	72.81
5	4	464.28	5,319.68	32.47
5	14	451.59	5,319.68	112.59
15	9	1,365.08	5,158.04	216.21
15	4	1,378.73	5,158.04	96.41
15	14	1,341.04	5,158.04	334.36

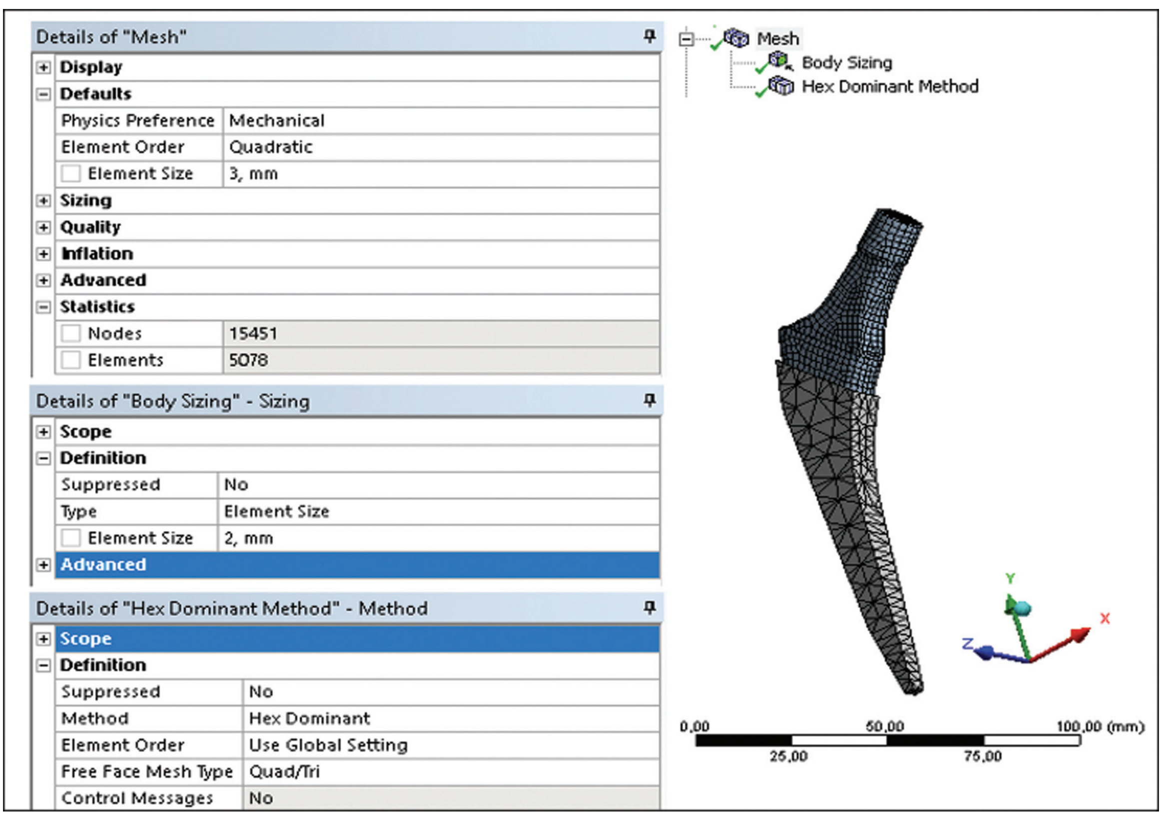

Fig. 6 Finite element (mesh) model.
Source: Author's collection.

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Table 3 Mesh convergence

Tetrahedral fill region (mm)	Region of hexahedral interest (mm)	Number of knots/ Elements	Equivalent stress (MPa)
5 mm	4 mm	5,155/1,818	276.93
5 mm	3 mm	7,439/2,572	275.56
5 mm	2.5 mm	9,880/3,318	278
4 mm	2 mm	14,913/4,816	284.72
3 mm	2 mm	15,451/5,078	283.92
2 mm	**1.5 mm**	**28,908/9,508**	**328.67**

Table 4 Mesh convergence

α°	β°	Equivalent stress (MPa)	Main stress (MPa)	Strain (mm/mm)
10	9	291.69	283.92	0.00142
10	4	284.63	277.33	0.00139
10	14	299.15	290.93	0.00146
5	9	322.26	316.07	0.00158
5	4	318.72	312.77	0.00157
5	14	326.01	319.59	0.00160
15	9	258.88	254.53	0.00125
15	4	248.37	247.11	0.00120
15	14	270.01	262.53	0.00130

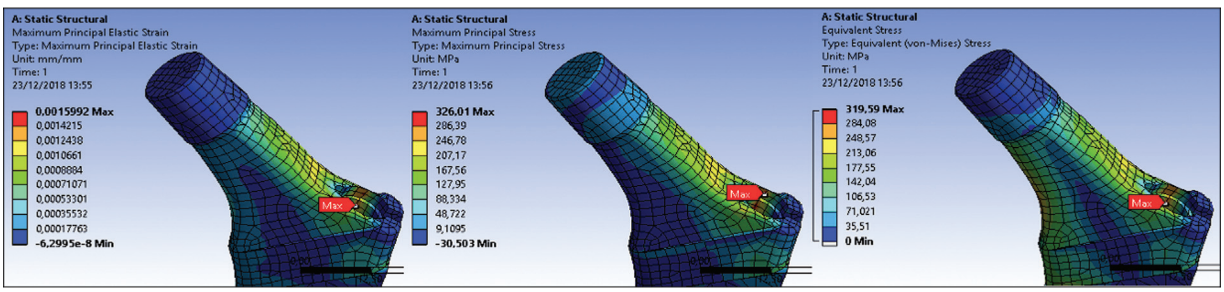

Fig. 7 Region with higher stress concentration.
Source: Author's collection.

cartilage, spongy bone, and cortical bone of the acetabulum and proximal femur, as well as their response to load simulations.

Regarding hip arthroplasties, in 2016, Reimeringer and Nuño[13] used FEM to study the behavior of the cementless femoral component in the femoral canal and demonstrated that total contact between the prosthesis and the host bone is not required for osteointegration; a contact from 25 to 57% allowed good bone integration. Bitter et al.,[14] in 2017, studied the wear on modular components of THA with FEM; they could adequately predict the expected annual wear rate of the prosthetic system compared to physical tests.

In 2019, Chethan et al.[15] used FEM to study the static physical structure of several models of femoral nails and acetabular components for THA and concluded that the trapezoidal femoral components suffer less strain; ceramic acetabular inserts, on the other hand, showed better mechanical properties under load. Finite element method was validated as an alternative method to traditional physical tests on hip prostheses by Delikanli and Kayacan[16] in 2019; their study compared the behavior of a titanium femoral stem under load in a physical model and FEM, with similar results.

Therefore, several studies show the great potential of FEM within orthopedics, especially in studies of the behavior of arthroplasties regarding various load simulations. Our study reinforces, from an experimental point of view, the importance of the correct positioning of the femoral component in THA to reduce the strain over the implant and possibly increase the long-term survival of the prosthesis.

As a limitation, this is an experimental study, serving only as a conduct guide for orthopedic surgeons. Long-term clinical follow-up studies are required to compare the survival of cementless prostheses implanted in an eccentric position or centered in the femoral canal.

Based on our findings, a potential future study would be to investigate the fatigue life of this femoral component at high tensions and compare it with the FEM analysis.

Conclusion

Varying the positioning of the prosthetic femoral stem in +/− 5° in the coronal plane and/or in the coronal and sagittal planes significantly interfered with the implant strain. Long-term clinical follow-up studies with cementless hip femoral prostheses are required to verify the influence of eccentric stem positioning on arthroplasty survival.

Financial Support

There was no financial support from public, commercial, or non-profit sources.

Conflict of Interests

The authors declare no conflict of interests.

References

1 Evans JT, Evans JP, Walker RW, Blom AW, Whitehouse MR, Sayers A. How long does a hip replacement last? A systematic review and meta-analysis of case series and national registry reports with

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more than 15 years of follow-up. Lancet 2019;393(10172):647–654
2 Bergmann G, Deuretzbacher G, Heller M, et al. Hip contact forces and gait patterns from routine activities. J Biomech 2001;34(07):859–871
3 Murray MP, Gore DR, Brewer BJ, Mollinger LA, Sepic SB. Joint function after total hip arthroplasty: a four-year follow-up of 72 cases with Charnley and Müller replacements. Clin Orthop Relat Res 1981;(157):119–124
4 ISO. 7206–4 Implants for surgery–Partial and total hip joint prostheses–Part 4: Determination of endurance properties and performance of stemmed femoral components. Vernier, Geneva Switzerland 2010. Disponível em: https://www.iso.org/standard/69125.html
5 ISO. 7206–6 Implants for surgery–Partial and total hip joint prostheses–Part 6: Endurance properties testing and performance requirements of neck region of stemmed femoral components. Vernier, Geneva Switzerland 2013. Disponível em: https://www.iso.org/standard/51186.html
6 Taylor M, Prendergast PJ. Four decades of finite element analysis of orthopaedic devices: where are we now and what are the opportunities? J Biomech 2015;48(05):767–778
7 Viceconti M, Toni A, Giunti A. Effects of some technological aspects on the fatigue strength of a cementless hip stem. J Biomed Mater Res 1995;29(07):875–881
8 Semenescu A, Radu-Ioniță F, Mateș IM, et al. Finite element analysis on a medical implant. Rom J Ophthalmol 2016;60(02):116–119
9 ASTM F1713–08(2013) Standard Specification for Wrought Titanium-13Niobium-13Zirconium Alloy for Surgical Implant Applications (UNS R58130) American Society for Testing and Materials. 2013
10 Ravaglioli A, Krajewski C, Eds. Bioceramica e Corpo. Faenza, Italy: Springer Science + Business Media; 1984
11 Goel VK, Nyman E. Computational Modeling and Finite Element Analysis. Spine 2016;41(Suppl 7):S6–S7
12 Akrami M, Craig K, Dibaj M, Javadi AA, Benattayallah A. A three-dimensional finite element analysis of the human hip. J Med Eng Technol 2018;42(07):546–552
13 Reimeringer M, Nuño N. The influence of contact ratio and its location on the primary stability of cementless total hip arthroplasty: A finite element analysis. J Biomech 2016;49(07):1064–1070
14 Bitter T, Khan I, Marriott T, Lovelady E, Verdonschot N, Janssen D. Finite element wear prediction using adaptive meshing at the modular taper interface of hip implants. J Mech Behav Biomed Mater 2018;77:616–623
15 K N C, Zuber M, Bhat N S, Shenoy B S, R Kini C. Static structural analysis of different stem designs used in total hip arthroplasty using finite element method. Heliyon 2019;5(06):e01767
16 Delikanli YE, Kayacan MC. Design, manufacture, and fatigue analysis of lightweight hip implants. J Appl Biomater Funct Mater 2019;17(02):2280800019836830

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