Pipkin Type-II Femoral Head Fracture: A Biomechanical Evaluation by the Finite-Element Method*

Fratura da cabeça femoral de tipo II de Pipkin: Avaliação biomecânica pelo método de elementos finitos

Anderson Freitas[1,2] Nathallie Campos Demeneghi[1] Fabrício Reichert Barin[2] Leonardo Rigobello Battaglion[3] Robinson Esteves Pires[4] Vincenzo Giordano[5]

[1] Hospital Regional do Gama, Brasília, Distrito Federal, Brazil
[2] Department of Orthopedics, Instituto de Pesquisa e Ensino, Hospital Ortopédico e Medicina Especializada (IPE-HOME), Brasília, Distrito Federal, Brazil
[3] Department of Orthopedics and Anesthesiology, Faculdade de Medicina de Ribeirão Preto, Universidade de São Paulo (FMRP-USP), Ribeirão Preto, São Paulo, Brazil
[4] Department of the Locomotor Apparatus, Faculdade de Medicina, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais Brazil
[5] "Nova Monteiro" Orthopedics and Traumatology Service, Hospital Municipal Miguel Couto, Rio de Janeiro, Rio de Janeiro, Brazil

Address for correspondence Anderson Freitas, MD, PhD, Instituto de Pesquisa e Ensino, Hospital Ortopédico e Medicina Especializada (IPE-HOME), SGAS Quadra 613–Conjunto C, Brasília, DF, 70200-730, Brazil (e-mail: andfreitas28@gmail.com).

Rev Bras Ortop 2023;58(3):507–513.

Abstract

Objective To evaluate the biomechanical capacity of two forms of fixation for Pipkin type-II fractures, describing the vertical fracture deviation, the maximum and minimum principal stresses, and the Von Mises equivalent stress in the syntheses used.

Materials and Methods Two internal fasteners were developed to treat Pipkin type-II fractures through finite elements: a 3.5-mm cortical screw and a Herbert screw. Under the same conditions, the vertical fracture deviation, the maximum and minimum principal stresses, and the Von Mises equivalent stress in the syntheses used were evaluated.

Results The vertical displacements evaluated were of 1.5 mm and 0.5 mm. The maximum principal stress values obtained in the upper region of the femoral neck were of 9.7 KPa and 1.3 Kpa, and the minimum principal stress values obtained in the lower region of the femoral neck were of -8.7 KPa and -9.3 KPa. Finally, the peak values for Von Mises stress were of 7.2 GPa and 2.0 GPa for the fixation models with the use of the 3.5-mm cortical screw and the Herbert screw respectively.

Keywords
- femoral head
- hip fractures
- bone screws

* *Work developed at Instituto de Pesquisa e Ensino, Hospital Ortopédico e Medicina Especializada (IPE-HOME), Brasília, Distrito Federal, Brazil.*

received
January 16, 2022
accepted after revision
July 26, 2022
article published online
October 3, 2022

DOI https://doi.org/10.1055/s-0042-1756326.
ISSN 0102-3616.

Thieme Revinter Publicações Ltda., Rua do Matoso 170, Rio de Janeiro, RJ, CEP 20270-135, Brazil

Conclusion The fixation system with the Herbert screw generated the best results in terms of reduction of vertical displacement, distribution of the maximum principal stress, and the peak Von Mises equivalent stress, demonstrating mechanical superiority compared to that of the 3.5-mm cortical screw in the treatment of Pipkin type-II fractures.

Resumo

Objetivo Avaliar a capacidade biomecânica de duas formas de fixação de fraturas tipo II de Pipkin descrevendo o desvio da fratura no sentido vertical, as tensões máxima e mínima principais, e a tensão equivalente de Von Mises nas sínteses utilizadas.

Materiais e Métodos Dois fixadores internos foram desenvolvidos para tratar a fratura tipo II de Pipkin por meio de elementos finitos: parafuso cortical de 3,5 mm e parafuso de Herbert. Sob as mesmas condições, foram avaliados o desvio da fratura no sentido vertical, as tensões máxima e mínima principais, e a tensão equivalente de Von Mises nas sínteses utilizadas.

Resultados Os deslocamentos verticais avaliados foram de 1,5 mm e 0,5 mm. Os valores de tensão máxima obtidos na região superior do colo femoral foram de 9,7 KPa e 1,3 KPa, e os valores de tensão mínima obtidos na região inferior do colo femoral foram de -8,7KPa e -9,3 KPa. Por fim, os valores de pico da tensão equivalente de Von Mises foram de 7,2 GPa e 2,0 GPa para os modelos de fixação com o uso do parafuso cortical de 3,5 mm e do parafuso de Herbert, respectivamente.

Conclusão O sistema de fixação com parafuso de Herbert gerou os melhores resultados em termos de redução do deslocamento vertical, distribuição da tensão máxima e do pico da tensão equivalente de Von Mises, o que demonstra sua superioridade mecânica comparada à do parafuso cortical de 3,5 mm no tratamento da fratura tipo II de Pipkin.

Palavras-chave
- cabeça do fêmur
- fraturas do quadril
- parafusos ósseos

Introduction

Despite their rare incidence (ranging from 8% to 26%) compared to that of other proximal or articular hip lesions, femoral head fractures, described in 1869,[1] have great clinical and scientific importance due to their surgical complexity and predisposition to the development of severe dysfunctions.[2] With an etiology linked to automobile accidents with high energy impact, they are usually accompanied by posterior hip displacements (ranging from 5% to 15%).[3,4] The conservative approach to treatment does not present good results, so open reduction and internal fixation is the main recommendation.[3,5] Surgical planning is dependent on the severity of the lesion, and it is initially guided by the Pipkin classification (from types I to IV)[1–6] (►**Fig. 1**).[7]

Type-II lesions present great controversy regarding approach and fixation models, with little scientific research.[2,3,8–11] Previous studies (case reports and retrospective analyses) show favorable results with the use of cortical screws of minifragment (measuring between 2.0 mm and 2.4 mm)[9] and Herbert screws.[8,10] On the other hand, despite their differentiated compression capacity compared to that of other syntheses and their wide clinical use, 3-mm canulated screws have been associated with a greater predisposition to develop osteoarthritis.[12]

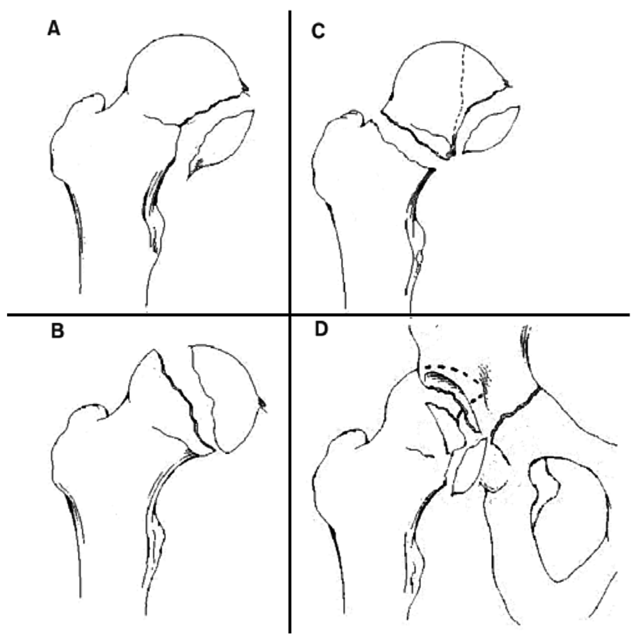

Fig. 1 The Pipkin classification. (**A**) Type I: fracture of the femoral head inferior to the central fovea. (**B**) Type II: fracture extended superiorly to the central fovea. (**C**) Type III: any fracture of the femoral head with associated femoral neck fracture. (**D**) Type IV: any fracture of the femoral head with associated acetabular fracture.[7]

The scientific foundation for the direction and surgical clinical planning of Pipkin type-II fractures is composed of case reports and longitudinal studies. The lack of mechanical tests based on validated methodologies makes it difficult to practice a solid evidence-based medicine, a tangible fact due to its low frequency. As far as we know, the biomechanical investigation of the treatment of Pipkin type-II fractures through the finite-element method (FEM) has so far been neglected. The possibility of performing complex biomechanical studies that enable the visualization of the mechanical performance of the synthesis and fracture under analysis demonstrates the potential and explains the use of the FEM.[13,14]

Thus, we aimed to evaluate the biomechanical ability of two forms of fixation of Pipkin type-II fractures (3.5 mm cortical screw and Herbert screw), describing the vertical fracture deviation, the maximum and minimum principal stresses, and the Von Mises equivalent stress in the syntheses used. The present is the first FEM biomechanical report comparing two treatments for Pipkin type-II fractures.

Materials and Methods

Dimensional Characteristics and Bolt Insertion Technique

The Herbert screw was formatted with a larger diameter of its threads, of 4.3 mm and 5.3 mm, distal and proximal respectively, and 3.3 mm in diameter in its body (threadless area). The 3.5-mm cortical screw, on the other hand, carefully respected the dimensional similarities for each structural part, sold by Depuy-Synthes (Raynham, MA, United States) (►**Figs. 2C** and **D**).

Analysis though the Finite-Element Method (FEM)

Tomographic images of a medium-sized synthetic femur (Sawbones, Vashon Island, WA, United States, fourth generation, model 3403-103, of 10 pounds per cubic foot (PCF) on the left side were used for the analyses.

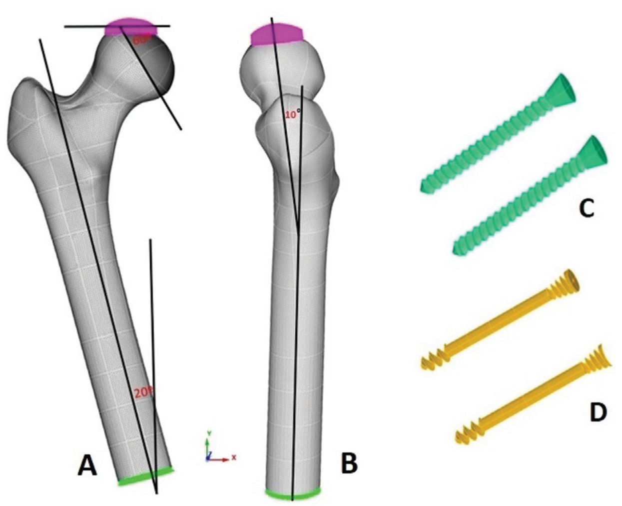

Fig. 2 Conditions and contours of the tests. (**A**) Frontal view. (**B**) Lateral view of a model representing a Pipkin type-II femoral head fracture and the position during the essay. Green area at the base of the femur: fixation point. Pink area on the femoral head: loading area. (**C**) 3.5-mm cortical screw. (**D**) Herbert screw.

In the study through the FEM, the materials used are divided according to their characteristics into ductile and non-ductile. Metallic materials, for example, the synthesis, belong to the ductile group, and their tension is measured by Von Mises equivalent stress test. However, the von Mises equivalent stress is not used in bone analysis, since bones belong to the non-ductile group of materials, and the maximum and minimum principal stresses are more suited for their evaluation.

We will now describe in detail the variables for the analysis of the von Mises equivalent stress and of the maximum and minimum principal stresses.

Von Mises equivalent stress: the stress of materials with metallic characteristics is measured by the Von Mises equivalent stress test, which consists of a magnitude proportional to the distortion energy used in failure tests of ductile materials in which the failure of the material is predicted, regardless of the stress/strain status, which means that the traction and compression stresses are considered equal and treated in the same way.

Maximum principal stress: for the analysis of the maximum principal stress, there is the traction force composed of load that corresponds to pulling the solid, and this type of forces presents positive values, so the traction force is composed of a load that intends to stretch or extend the solid.

Minimum principal stress: for the analysis of the minimum principal stress, the compression force is composed of load that corresponds to compressing the solid, and this type of force is conceptually represented by negative values, just to inform the opposite direction of its application in relation to the maximum principal stress.

Developing the Biocad

The three-dimensional (3D) virtual models of each system (bone, synthesis) were developed using the Rhinoceros (Robert McNeel & Associates, Seattle, WA, United States) software, version 6, and the FEM analysis was performed in the Altair SimLab (HyperWorks, Troy, MI, United States) software using the Altair Optistruct solver.

Based on the models of synthetic bones, tomographic images of the bone were obtained and saved following in the Digital Imaging and Communications in Medicine (DICOM) protocol. We used the 16-channel Emotion tomograph (Siemens Healthineers, Erlangen, Germany) with a resolution of 512 × 512 and a distance of 1.0 mm between cuts. The DICOM file was imported to the InVesalius (Software livre do Centro de Tecnologia da Informação Renato Archer, Campinas, SP, Brasil) software for the 3D reconstruction of the anatomical structure. Based on a set of two-dimensional imagesd obtained through computed tomography equipment, the software enables the development of 3D virtual models of the regions of interest of the system imported there (►**Fig. 2**). After the 3D reconstruction of the DICOM images, the software enables the creation of 3D files in the format called stereo lithography or standard triangle language (STL).

File Conversion

In the InVesalius software, all the slices were imported to obtain the STL file with the images that would be used in the process of obtaining the 3D solid, and with this there is the option of multiplanar generation that shows the sagittal, coronal, and axial views, and the volume. The development of the 3D surface is based on the volume, in which one may select the regions of interest using masks and/or filters, which cause the file to be hidden or portrayed according to the algorithm in question, thus generating the 3D surface.

Simulation

The FEM was used for the simulations of the stability of the different assemblies. First, the files were imported to the Altair Simlab software, with the identification of each part of the digital models.

Material Properties

To perform the simulations, one must know and define the properties of the materials of each part of the digital models, which are the cortical bone, the trabecular bone, and the steel alloy. The properties of the materials used for the simulations are the modulus of elasticity and the Poisson coefficient (►**Table 1**).

Boundary Conditions

To define the boundary conditions, a load of 6,000 N was applied to the upper region of the femoral head in the direction of the Z axis. No load was applied to the X and Y axis. Loading was performed with the positioning of 20° of posterior inclination and 0° in the axial axis, maintaining the physiological 10° of anteversion of the femoral neck. Subsequently, the movement restriction regions (fixed) were delimited, marked in all directions of the X, Y, and Z axes, of displacement and rotation. These restrictions are to ensure that the system has a perfect alignment without displacement and/or rotation (►**Figs. 2A** and **B**).

After the control of the meshes of each part, care should always be taken to preserve the size of the element, so that there are no contact issues between different parts (femur and synthesis) in the simulations. The element adopted for mesh formation was tetrahedral. The number of nodes was also established.

Table 1 Properties of the materials used in the present study

Material	Properties	
	Modulus of Elasticity and (MPa)	Poisson coefficient (v)
Cortical bone	17	0.26
Trabecular bone	1.7	0.26
Syntheses (steel)	193	0.33

Source: Markus, AT, Miguel LFF. Simulation of human humerus fracture using the discrete elements method. Computational Mechanics 2008;45:3411-3422.

Analysis Criteria

The displacement of the models and the specific displacement of each fragment were analyzed through the FEM. For the analysis of the stress in the non-ductile materials (bone and fracture), we used the variables maximum principal stress (traction) and minimum principal stress (compression). For the ductile (metallic) materials, the stress analyzed was the Von Mises equivalent stress.

The variables maximum and minimum principal stresses and Von Mises equivalent stress are principles of matter presented in the form of tension. The unit of measurement for stress is the Pascal (Pa), and the stress forces are measured in megapascals (MPA) and gigapascals (GPa).

The results were expressed as absolute values and percentiles through following the equation: higher value $\times$ X = lower value $\times$ 100 (simple rule of 3), and the final percentile value equals 100–X.

Results

Description of the Vertical Fracture Displacement in the Different Fixation Models

The vertical displacements evaluated were of 1.5 mm and 0.5 mm for the fixation models using the 3.5-mm cortical screw and Herbert screw respectively (►**Fig. 3**).

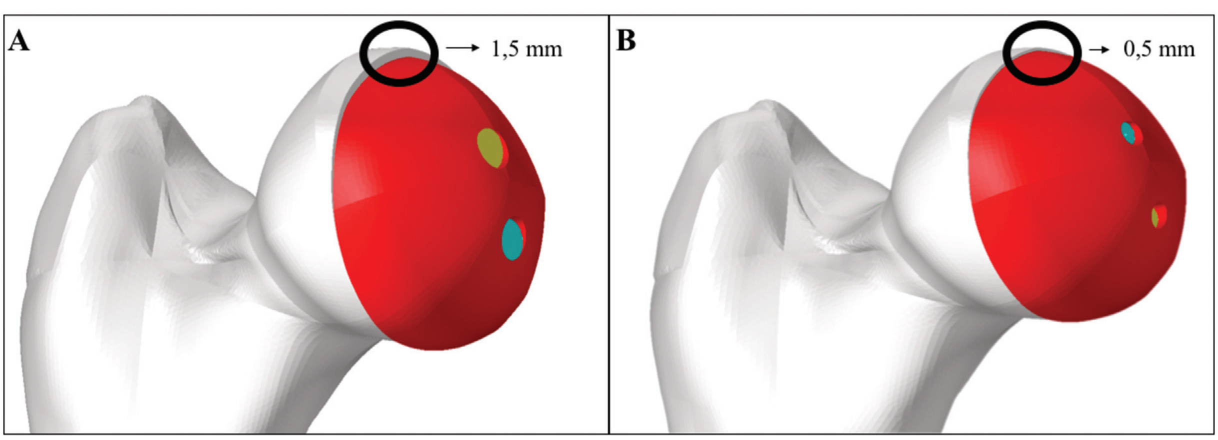

Fig. 3 Description of the vertical displacement of the fracture with the different fixation models. (**A**) 3.5-mm cortical screw (displacement: 1.5 mm). (**B**) Herbert screw (displacement: 0.5 mm).

We observed that the Herbert screw reduced the vertical displacement at a rate of ~ 66.6% in Pipkin type-II femoral head fractures.

Distribution of Maximum (Traction) and Minimum (Compression) Principal Stresses in Fractures in the Different Fixation Models

The values for the maximum principal stress obtained in the upper region of the femoral neck, adjacent to the fracture, were of 9.7 KPa and 1.3 KPa for the fixation models with the use of the 3.5-mm cortical screw and Herbert screw respectively (►**Figs. 4A** and **B**), representing a reduction of 87% in the local tension and a better distribution with the use of Herbert screw.

The values for the minimum principal stress obtained in the lower region of the femoral neck, adjacent to the fracture, were of -8.7 KPa and -9.3 KPa for the fixation models with the use of the 3.5-mm cortical screw and Herbert screw respectively (►**Figs. 4C** and **D**), representing an increase of 6.4% in the local tension with comparable distribution using the Herbert screw.

Distribution of the Peak Von Mises Equivalent Stress in the Different Fixation Models

The peak values for the Von Mises equivalent stress were of 7.2 GPa and 2.0 Gpa for the fixation models with the use the 3.5-mm cortical screw and Herbert screw respectively. The reduction observed with the Herbert screw was of approximately 72.2%. Moreover, the synthesis models presented their largest area of tension in the fracture line, a site that represents a greater concern in the synthesis fracture (►**Fig. 5**).

Discussion

Fractures of the femoral head have historically been associated with controversial results that depend on the synthesis used. Internal fixation must ensure stability, preferably with compression between the fracture fragment and the rest of the femoral head.[3] Because it is a rare fracture, experimental or computational mechanical essays are extremely important, for they provide data that assist in the outcomes of the patients. The FEM has been proven to be an efficient methodology for biomechanical research in the field of bone fractures.[14,15]

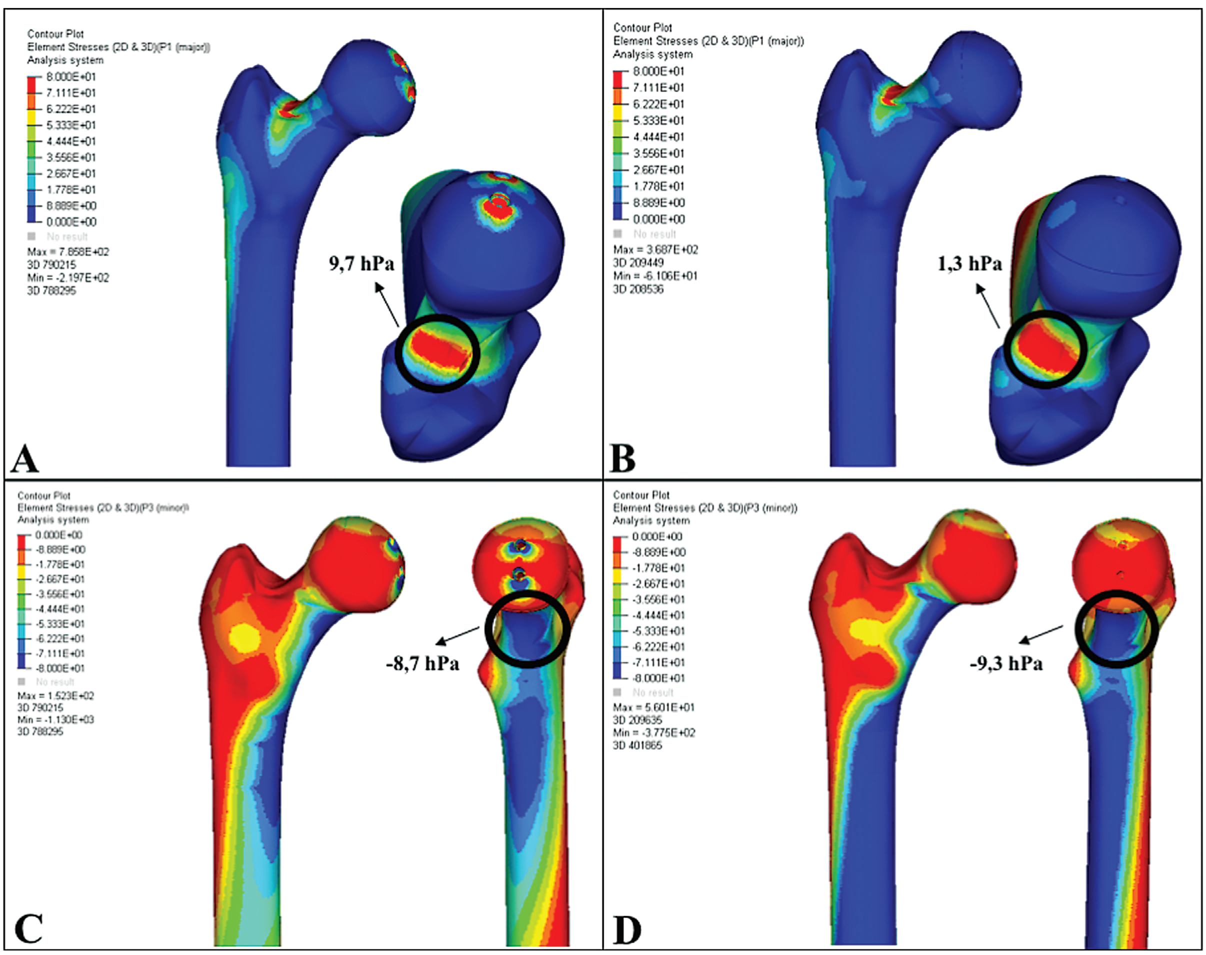

Fig. 4 Distribution of the maximum principal stress in fractures with the different fixation models. (**A**) 3.5-mm cortical screw: 9.7 KPa. (**B**) Herbert screw: 1.3 KPa. Distribution of the minimum principal stress in fractures with the different fixation models. (**C**) 3.5-mm cortical screw: -8.7 KPa. (**D**) Herbert screw: -9.3 KPa.

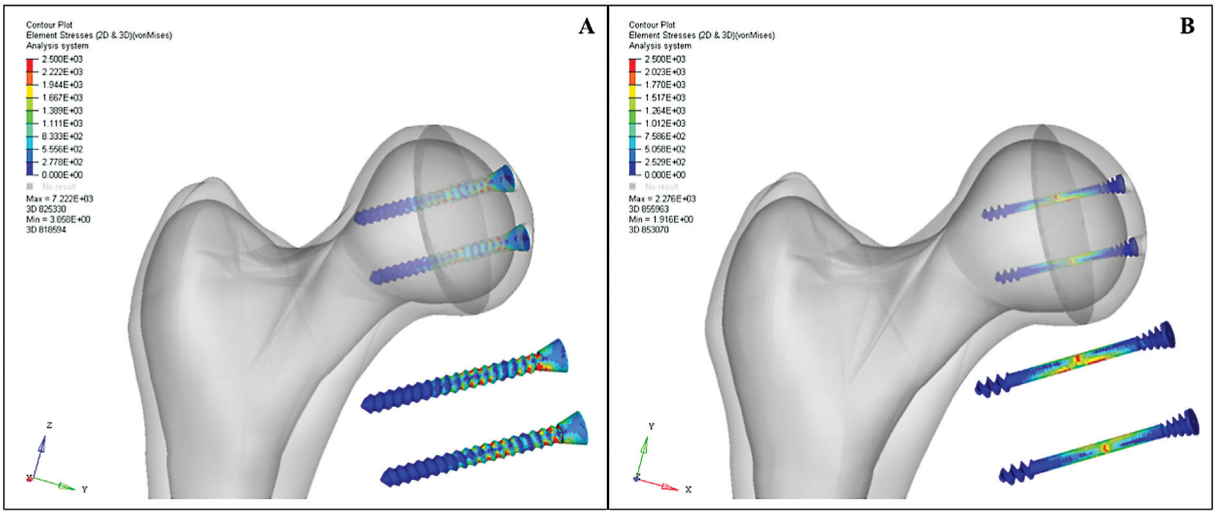

Fig. 5 Distribution of the peak Von Mises equivalent stress in the different fixation models. (**A**) 3.5-mm cortical screw: 7.2GPa. (**B**) Herbert screw: 2.0 GPa.

Thus, through the FEM, we evaluated the vertical dsplacement of the fracture, the maximum and minimum principal stresses, and the Von Mises equivalent stress of 2 syntheses (3.5-mm cortical screw and Herbert screw) widely used in the treatment of Pipkin type-II fractures. As far as we know, the present is the first FEM model in Pipkin type-II fractures, and the first study comparing treatments using biomechanical methods. Our results show the superiority of the Herbert screw, which causes a reduction decrease in the vertical displacement and the distribution of the maximum principal stress and the peak of the Von Mises equivalent stress.

The search for syntheses that promote adequate internal fixation, enabling early mobilization and thus contributing to good clinical results was the focus of previous clinical research, which pointed in the same direction as the biomechanical results of the present study, demonstrating the positive effects of the Herbert screw on Pipkin type-II fractures. In 1988, Murray et al.[10] performed open reduction and internal fixation with the Herbert screw in an osteochondral fracture of the femoral head. After twelve months, the results showed an excellent hip function and no radiographic evidence of avascular necrosis. More recently, Zaizi et al.[8] reported good results with the treatment of Pipkin type-II fractures using anatomical reduction and internal fixation by means of two Herbert screws, after two years of follow-up. Wang et al.,[11] in a prospective analysis of three patients treated using Herbert screws, reported results of satisfactory hip function assessed by the modified Merle d'Aubigné score.

Despite the numerous clinical difficulties regarding the treatment of fractures in load-bearing joints, the possibility of compression inherent to the characteristic of the differences in the threads (distal and proximal) of the Herbert screw, and that for this it needs to have a larger diameter in relation to the 3.5-mm screw, we were able to experimentally confirm its biomechanical advantage.[10] Furthermore, our results suggest that the ability to distribute stress and decrease fracture dislocation are relevant factors to understand the mechanical effectiveness of the Herbert screw. One of the indirect objectives of the present study was to qualitatively analyze the close relationship between synthesis material and bone structure using the interfragment compression technique. The close contact of the Herbert screw due to the lack of need for a smooth tunnel in its technique (unlike the 3.5-mm screw) seems to be a hypothesis for its better biomechanical results, and it may also make a difference in terms of fracture stability in the reabsorption phase of the fractured edges. Future studies need to improve the methodology to perform a more accurate evaluation and determination of this clinical hypothesis (►**Fig. 6**).

The present is the first study to use the FEM to compare different fixation methods, analyzing complex biomechanical variables (peak Von Mises equivalent stress and compression and traction distribution in fractures) in Pipkin type-II fractures. The present study has certain limitations that should be highlighted. The lack of effects of muscle and ligament on fracture stability, bone quality and possible individual differences in terms of gender, ethnicity, age, and previous diseases were not taken into account during the analyses. These limitations should be evaluated in future clinical manuscripts.

Conclusion

The fixation system with the Herbert screw yielded the best results in terms of reduction of the vertical displacement, distribution of the maximum principal stress and peak Von Mises equivalent stress, demonstrating its mechanical superiority compared to the 3.5-mm cortical screw in the treatment of Pipkin type-II fractures.

Financial Support
The authors declare that they have received no financial support from public, commercial, or non-profit sources pertaining to the conduction of the present study.

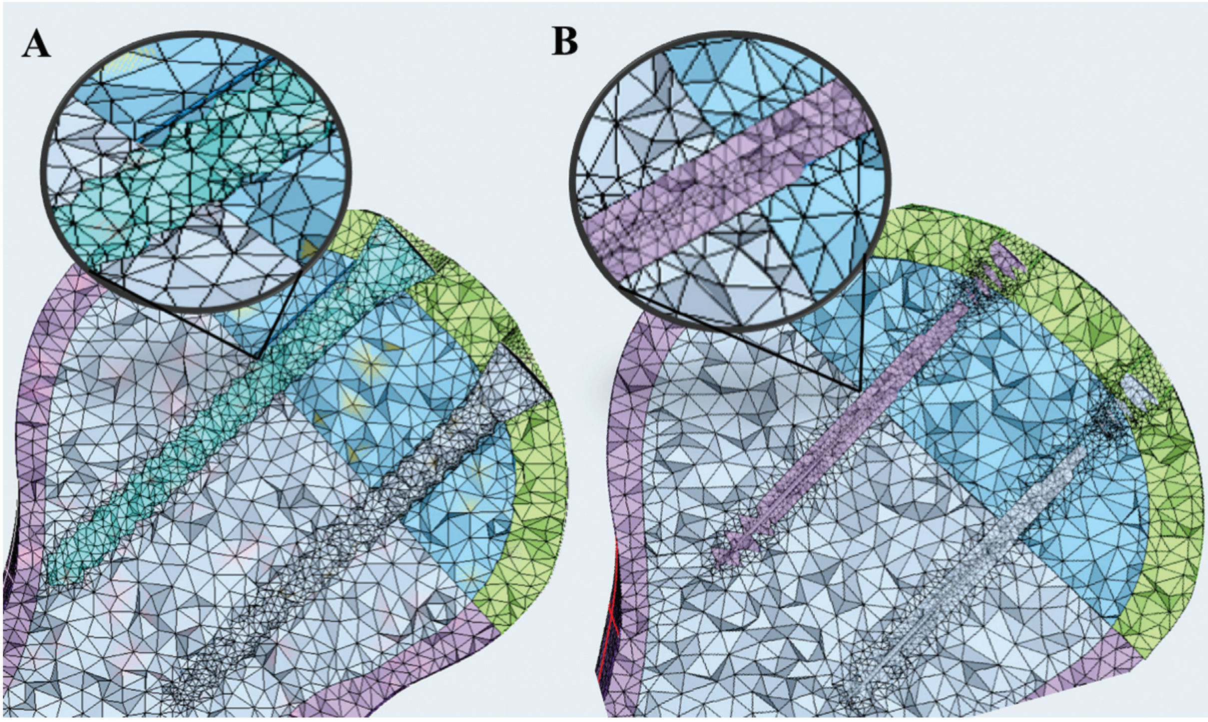

Fig. 6 Qualitative analysis of the relationship between synthesis material and bone structure. (**A**) close relationship between the Herbert screw and bone structure. (**B**) The need for a smooth tunnel in the interfragment compression technique with the 3.5-mm cortical screw does not yield the same degree of relationship observed between synthesis and bone structure with the Herbert screw.

Conflict of Interests
The authors have no conflict of interests to declare.

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