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STATE OF STRESSES IN 2D OSTEOPOROTIC MODELS ACCORDING TO HUMAN PROXIMAL FEMORAL BONE AREA IN UNIPODAL SUPPORT

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Abstract: *This study aims to evaluation of the state of mechanical stresses and strains in osteoporotic 2D models corresponding to the zone of proximal human femoral bone. Osteoporotic 2D models is comply Singh index which characterizes the evolution of osteoporosis. Experimental models are made of epoxy resin and silicone rubber and are under mechanical loading (Instron testing machine) so that it is respected unipodal support. It uses experimental (digital image correlation) and numerical (finite element) analysis methods of the state of stresses and strains in the plane model. Results obtained by comparative analysis of osteoporotic 2D models highlights the migration of maximum loading area from the small trochanter (corresponding to a trabecular and cortical healthy structure) to the area of the bottom of the femoral neck (corresponding to a trabecular and cortical osteoporotic structure). The analysis of stresses and strains state of osteoporotic 2D models, which highlights the maximum sections mechanical loaded, have great relevance given that the incidence of fractures caused by osteoporosis is extremely high.*

Key words: *human femoral bone, bone architecture, osteoporosis, 2D osteoporotic models, Singh index, digital image correlation, finite element method, mechanical stress, deformations, epoxy resin, silicone rubber*

1. INTRODUCTION

A thorough knowledge of the relationship between bone mass, trabecular architecture structure and role of bone structure is fundamentally required for the development of new therapies for osteoporosis. It should be noted that with the evolution of osteoporosis [1, 2, 3, 4, 5] trabecular pattern from proximal femur register regression in a predictable sequence, generating state of stresses and strains [6, 7, 8] which may lead to increased risk of fractures [9]. There are a multitude of studies, with relevance, highlighting the state of stress and strain from human proximal femur using different methods of investigation: analytical [10], numerical – finite element [11, 12, 13, 14] and experimental [15, 16, 17, 18, 19]. The major concern of these studies is to understand how the femur behaves under mechanical stress action (support bipod [20], unipodal [21] or in the event of accidents [12]). Can be identified so many approaches to study: mechanical tests on real models, mainly aiming at determining the mechanical characteristics of cortical and trabecular structure [9, 14, 22, 23, 24, 25]; numerical modeling (3DµFE, FEA) of scanned models using different medical imaging systems (CT, µCT) [17, 26, 27, 28, 29]. All these approaches don't highlights very clear how trabecular structure considered "normal" or affected by osteoporosis take mechanical stresses to highlight dangerous sections.

The objective of this study is to determine the state of stress and strain in proximal femoral bone affected by osteoporosis based on a 2D model [21, 30]. It is considered a 2D model that has a number of 170 trabeculae forming a trabecular structure that comprises main and secondary compression groups, main and secondary tensile groups, ligamentous group and of growth lines. Based on the hierarchy Singh index [1] is suggested several osteoporotic models, trabecular structure was gradually affected: 12, 47, 56, 82 and 104 trabeculae. In a percentage expression we have: 7.05, 27.6, 32.9, 48.2 and 61.1% affected trabeculae (Fig. 1). Highlighting how the trabecular structure, affected by osteoporosis, take the mechanical stress from unipodal support is performed using the finite element method (FEA) and digital image correlation (DIC) technique. It is intended that by the two methods used, by the results achieved, validate a 2D model useful for applications in which the proximal area presents various fractures.

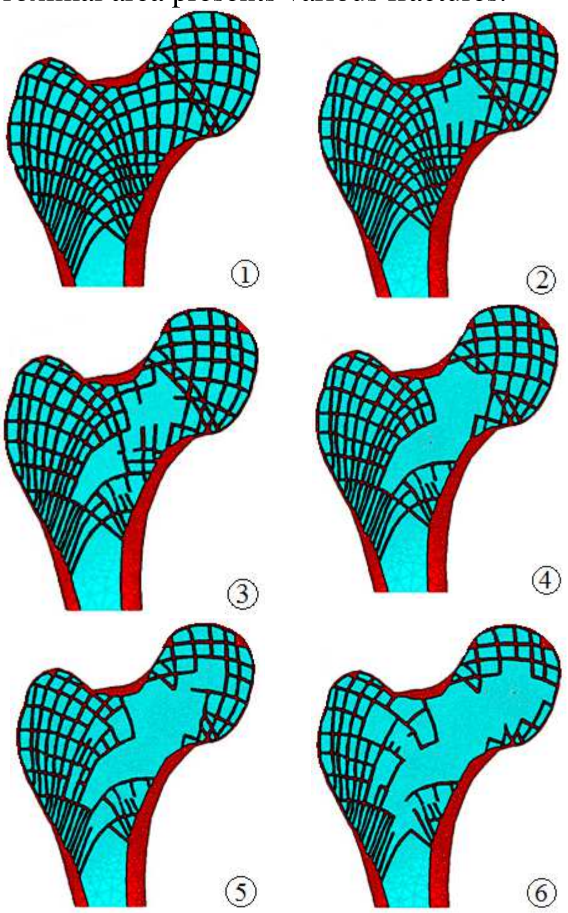


Fig.1 Regression of the trabecular structure from human proximal femur.

2. METHODS

2D PHYSICAL AND NUMERICAL MODELS

2D physical model is defined having as a reference element analysis of trabecular tissue distribution from proximal human femoral bone, cut longitudinally (from terms of local reference plane) as shown in Figure 2. Human femoral bone was received, by donation, from Department of Orthopaedics and Traumatology –" Alexandru Rădulescu", Cluj-Napoca, Romania.

Based on this study, a mold made of silicone rubber. Poured epoxy resin, is obtaining a plane model showing a trabecular architecture with the lollowing elements: ligamentous group, growth lines, primary and secondary tensile group, primary and secondary compression group or, in another speech, the plane model containing 14 tensile lines, 15 lines of compression and two lines that forming growth area resulting, in total, a number of 170 trabeculae, as shown in Figure 3.

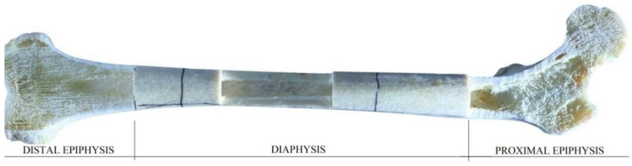


Fig.2 Human femoral bone cut longitudinally.

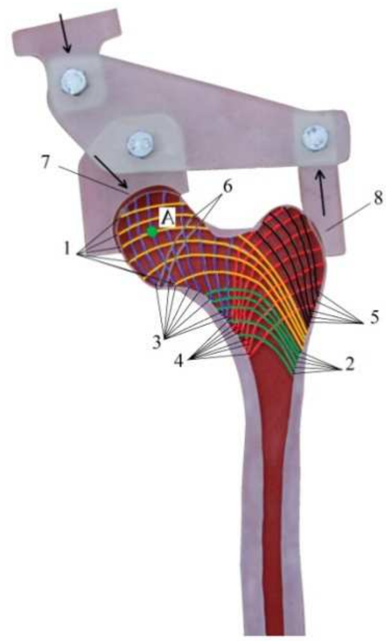


Fig.3 Referential 2D model elements: 1 – the main tensile group; 2 – the secondary tensile group; 3 – the main group of compression; 4 – the secondary compression group; 5 – ligamentous group; 6 – growth lines; 7 – hip joint; 8 – small and medium gluteal muscle insertion.

The average thickness of the lines forming trabecular architecture is 0.62 mm and for cortical structure is between 0.64 and 7.96 mm. The modulus of elasticity (Young modulus) of the epoxy resin used is 2.200 MPa and the transverse contraction factor is 0.36. The space that him formed the trabeculae is filled with silicone rubber for which Young modulus is 8MPa and transverse contraction factor is 0.47.

Taking as reference element the hierarchy of Singh index for evolution of osteoporosis are physically made four models which trabecular architecture is gradually affected. In Figure 4 are presented 3 models with the following configuration: the referential model (170 trabeculae), osteoporotic model with 12 trabeculae affected (7.05%), osteoporotic model with 47 trabeculae affected (27.6%). Is denoted by OP osteoporotic models.

Fig.4 2D physical models: 1 – referential model; 2 – OP model with 12 trabeculae affected; 3 – OP model with 47 trabeculae affected.

2D numerical models (Fig.1.1, Fig.1.2 and Fig.1.3) are dimensionally identical to those made physically – as shown in Figure 4. Defining 2D models is achieved through nodes, to which positioning using a Cartesian coordinate system. Numerical modeling implied use to finite elements with six triangular nodes and semicircular sides. For a more complete assessment of the state of stress and strain are defined, additional, 3 osteoporotic numerical models presenting the following configuration: 56 trabeculae affected (32.9%), 82 trabeculae affected (48.2%) and 104 trabeculae affected (61.1%) according to Figure 1.4, Figure 1.5 and Figure 1.6. Table 1 details the number of finite elements used for the six models considered.

EXPERIMENTAL AND NUMERICAL ANALYSIS OF 2D MODELS

The mechanical load system is designed to take account the action of hip joint (femoral head) and muscle action: gluteus medius and gluteus minimus – the greater trochanter area.

Table 1

Number of finite elements used for the 6 2D models.

Model	Trabeculae affected		Number of finite elements
	number	%	
Fig.1.1, Fig.4.1	Referential model – 170 trabeculae		6,877
Fig.1.2, Fig.4.2	12	7.05	6,915
Fig.1.3, Fig.4.3	47	27.6	6,943
Fig.1.4	56	32.9	6,871
Fig.1-e	82	48.2	6,625
Fig.1-f	104	61.1	6,683

Such a system of mechanical load is equivalent to a single leg support (unipodal support). In support unilateral or unipodal, hip joint is the point of support for the entire weigh of the human body, thus making unilateral support to be the most dangerous position. Here the femoral bone it is stabilized in the acetabulum by the abductor muscle group: small, medium and large gluteal muscle. For mechanical loading of 2D models is used the universal testing machine, Instron 3366 model, as shown in Figure 5.

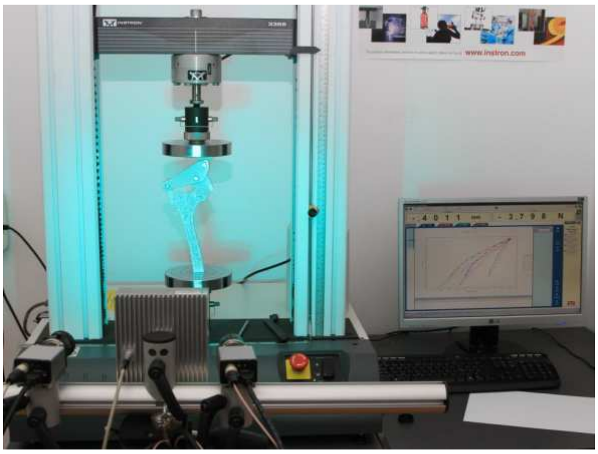


Fig.5 2D model is loaded mechanically through universal testing machine Instron 3366 and analyzed by digital image correlation method with Q400 system.

Is performed static mechanical loading, progressive with forces between 1 and 10 newton. The load pattern is represented in Figure 6. For each value of the applied force (1, 2, 3,..., 10 newtons) defines a constant load plateau has a duration of 20 seconds, in this time frame is recorded 2D model image.

These images are recorded by the Q400 system (Dantec Dynamics), analysis of displacement field being achieved through digital image correlation method using Istra 4D software. It will assess the movement in the vertical plane (dy) of the femoral head center, marked by the point A, as shown in Figure 3. Digital image correlation technique is a flexible and useful for analyzing deformation. It is important that the surface of the 2D models is sufficiently large, in this case the surface is approximately 20x9 cm, so that the digital image correlation algorithm should enable the identification field points to the two CCD cameras. This algorithm is based on identifying gray areas. For this reason 2D models surface is painted white over which generates a cloud of black dots, as shown in Figure 7.

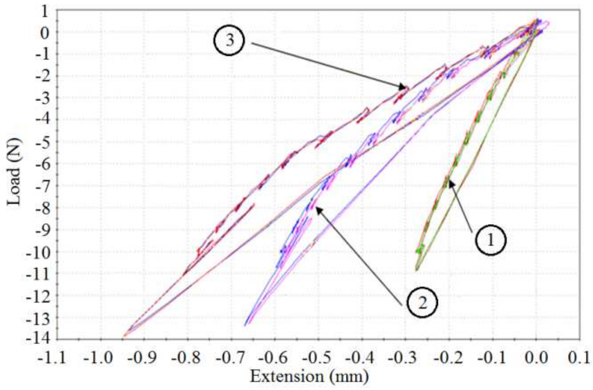


Fig.6 Mechanical load chart for 2D models: 1 – referential model; 2 – OP model with 12 trabeculae affected; 3 – OP model with 47 trabeculae affected.

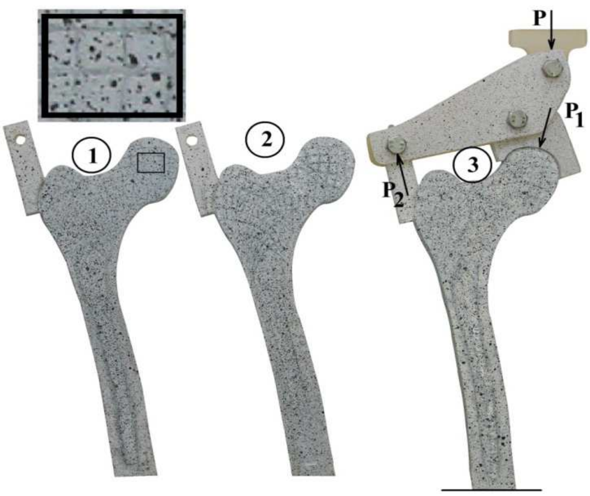


Fig.7 The cloud of points generated on the surface of 2D models: 1 – referential model; 2 – OP model with 12 trabeculae affected; 3 – OP model with 47 trabeculae affected.

2D models area is virtual divided into a set of facets able to be deformed under the action of mechanical loading in a variety of ways. By varying parameters of light and affine transformation parameters measurement accuracy is 0.01 pixels. Once determined 2D contour surface deformations can be calculated. This is achieved by correlating the images obtained with the two CCD cameras in relation to the reference image, when the 2D model is mechanical loaded. Knowing the displacement vectors of each point on the surface and the contour of reference, deformation can be calculated using specific deformation tensor (Lagrange) expressed by the following relations [31]:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \sum_{l=1}^{3} \frac{\partial u_l}{\partial x_i}\frac{\partial u_l}{\partial x_j}\right) \quad (1)$$

$$\varepsilon_{11} = \frac{\partial u_1}{\partial x_1} + \frac{1}{2}\left[\left(\frac{\partial u_1}{\partial x_1}\right)^2 + \left(\frac{\partial u_2}{\partial x_1}\right)^2 + \left(\frac{\partial u_3}{\partial x_1}\right)^2\right] \quad (2)$$

$$\varepsilon_{22} = \frac{\partial u_2}{\partial x_2} + \frac{1}{2}\left[\left(\frac{\partial u_1}{\partial x_2}\right)^2 + \left(\frac{\partial u_2}{\partial x_2}\right)^2 + \left(\frac{\partial u_3}{\partial x_2}\right)^2\right] \quad (3)$$

$$\varepsilon_{12} = \varepsilon_{21} = = \frac{1}{2}\left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} + \frac{\partial u_1}{\partial x_1}\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1}\frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_1}\frac{\partial u_3}{\partial x_2}\right) \quad (4)$$

Calibration of CCD cameras has a major influence on system performance. Are determined the following parameters:

- intrinsec parameters: focal length {x, y}: {3500 ± 600, 3500 ± 600}, principal point {x, y}: {720 ± 160, 530 ± 70}, radial distortion {r^2, r^4}: {-0.33 ± 0.18, 10 ± 30} and tangential distortion {t_x, t_y}: {-0.002 ± 0.003, -0.002 ± 0.014};
- extrinsec parameters: rotation vector {x, y, z}: {3.07 ± 0.02, -0.3133 ± 0.0017, -0.24 ± 0.04} and translation vector {x, y, z}: {0 ± 40, -11 ± 16, 770 ± 130}.

Numerical, analysis of 2D models is achieved by finite element method using RDM 6.15 software where are defined in cartesian coordinates nodes that allow tracing the contour, it makes meshing and in the distal area of the model is block all degrees of freedom.

3. RESULTS

The 2D referential model as well as two osteoporotic models (with 12 and 47 bays affected) can be validated by determining the vertical displacement (dy) of the center of the femoral head (point A in Fig.3) both the experimental (using digital image correlation method) and numeric (through finite element analysis). In Figure 8 are represented the values of displacement dy of the point A depending on the force P. From the analysis results can be seen that the average relative deviation in the case of the referential model (1 DIC and 1 FEA) is 10.645%, for osteoporotic model with 12 trabeculae affected (2 DIC and 2 FEA) is 9.366% and for osteoporotic model with 47 trabeculae affected (3 DIC and 3 FEA) is 5.655%. In light of these results it can be concluded that the models have a predictable behavior which enables numerical modeling and other osteoporotic 2D models with a greater number of bays affected, according to Figure 1.

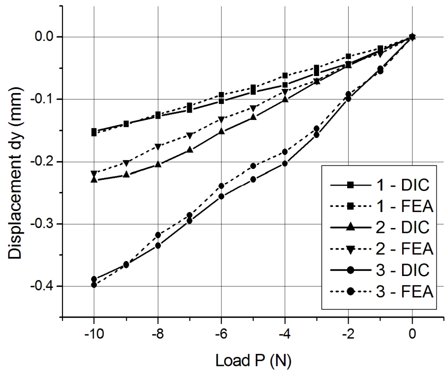


Fig.8 Displacement of femoral head center (dy) in function of the load P.

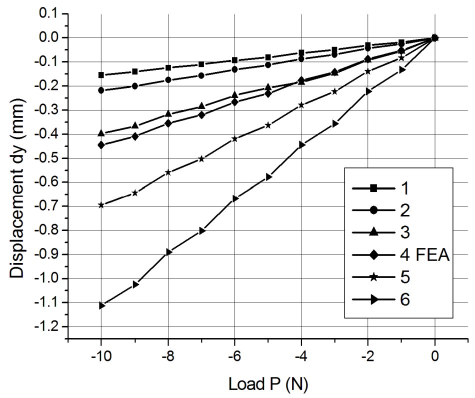
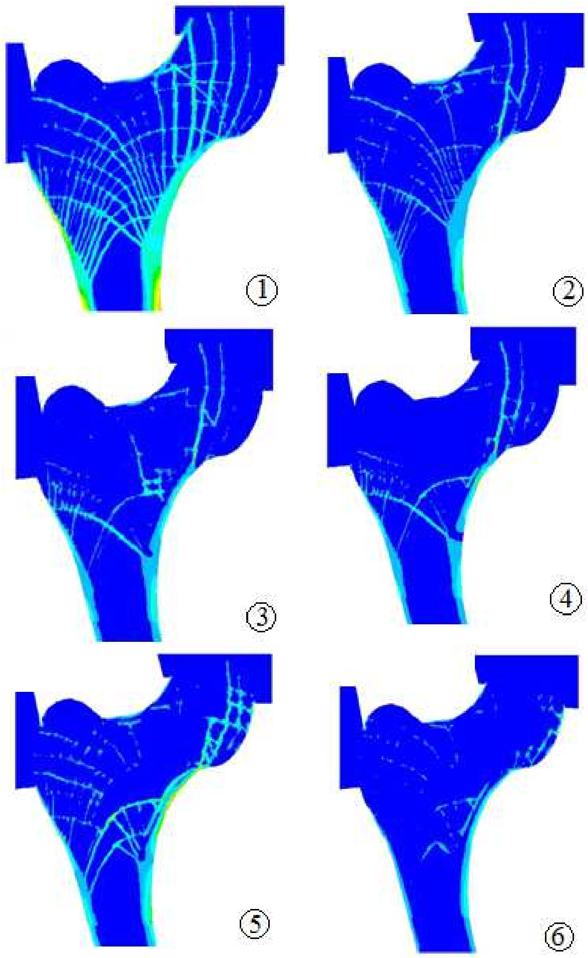


Fig.9 Displacement the femoral head center (point A) depending on the load P (FEA).

To assess the state of stresses and displacement of trabecular structure affected by osteoporosis is necessary to conduct a comparative analysis of the 5 osteoporosis 2D models, defined in Figure 1, in relation to 2D referential model. Thus, in Figure 9, Figure 10, Figure 11 and Figure 12 are synthetically presents displacement values in relative to the axis y (dy) of the femoral head center (point A), Tresca equivalent stresses (σ_{ech}) as well as maximum and minimum principal stresses (σ_1 and σ_2).



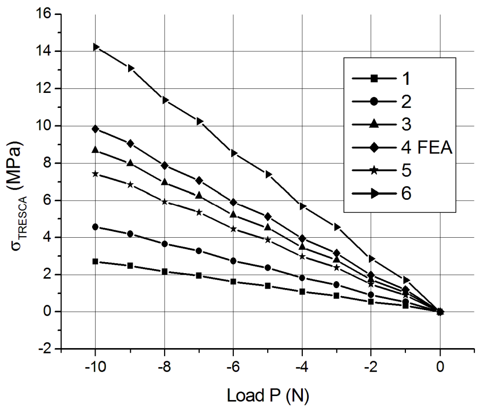


Fig.10 Tresca equivalent stresses σ_{ech} variation depending on the load P (FEA).

4. DISCUSSION AND CONCLUSIONS

The data presented in Figure 9 it may be noted that as the trabecular structure is affected the displacement dy of point A is progressively increased so, for example, if the trabecular structure is affected in proportion of 61.1% (2D OP model – with 104 trabeculae affected) compared to displacement of 2D referential model, in absolute terms, it is about 7 times higher. Such a situation is extremely dangerous because it can affect the structural integrity of the proximal femur and the hip joint.

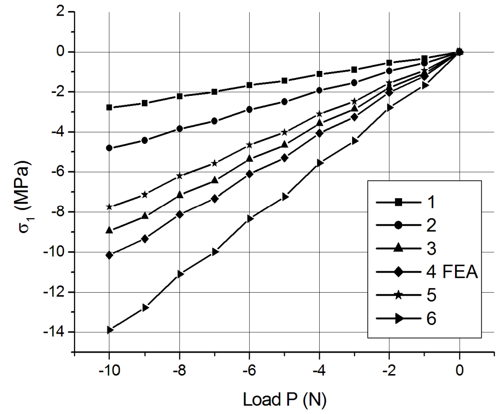


Fig.11 Principal stresses σ_1 variation depending on the load P (FEA).

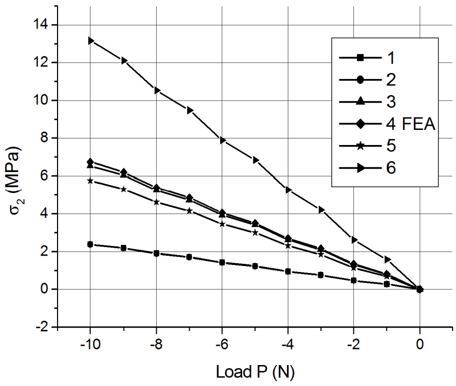


Fig.12 Principal stresses σ_2 variation depending on the load P (FEA).

The data presented in Figure 10 is observed that if the trabecular structure is not affected by osteoporosis equivalent stresses Tresca have maximum values in the area between diaphyseal femur and proximal element (small trochanter area). This area has a very high resistance because the cross section is annular, with an increased wall thickness, and cortical structure is predominant. As the trabecular structure is affected by osteoporosis maximum values of equivalent stresses Tresca migrate to the area of the bottom of the femoral neck, the area can fracture occurs. Compared to 2D referential model Tresca equivalent stresses is about 5 times higher in 2D OP model with 104 trabeculae affected (61.1%).

The data presented in Figure 11 is highlighted, through the principal stresses σ_1, how the trabecular structure takes over compressive stresses. It can be seen, as in the case of Tresca equivalent stresses, that the area where there is a principal stresses σ_1 is the small trochanter, for 2D referential model. As the trabecular structure is affected the maximum loaded area migrate to the femoral neck. Compared to 2D referential model principal stresses σ_1 is about 5 times higher in 2D OP with 104 trabeculae affected (61.1%).

The data presented in Figure 12 is highlighted, through principal stresses σ_2, how elements of the trabecular structure take the tensile efforts from proximal femur area as it is progressively by osteoporosis. It notes that if in the case of the 2D referential model maximum load is between the side diaphy to the greater trochanter (corresponding cortical structure), with the evolution of osteoporosis principal stresses σ_2 migrate to trabecular structure elements. Compared to 2D referential model principal stresses σ_2 is about 5.5 times higher in 2D OP with 104 trabeculae affected (61.1%).

The study of stresses and displacements from the proximal femur is particularly complex. There have been multiple concerns, representative, for example [5 and 6], which reveal the behavior of trabecular structure under mechanical load in two separate cases: health trabecular structure and trabecular structure affected by osteoporosis. With the development of various medical imaging equipment, in particular the case of micro computed tomography (μCT) and numerical methods of structural analysis (3DμFE) amounted need to operate with extremely high performance computing systems involving, unfortunately, extremely high times, of the order of weeks, to access the results can, sometimes, be inconclusive. This study presents a 2D model which is based on the analysis of a real model. The way to generate 2D model is relatively complex and the tools used to highlight the state of stresses and strains (digital image correlation method and finite element method) are generally accessible. It should be noted that access to relevant information can be realized in a much shorter time. This 2D model can be used in future studies to analyze the state of stresses and strains in case of bipod support.

5. ACKNOWLEDGEMENTS

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Starea de tensiuni şi deformaţii în modele osteoporotice 2D corespunzătoare zonei proximale a osului femural uman în sprijin unipodal

Rezumat: *În acest studiu se urmăreşte stabilirea stării de tensiuni şi deformaţii în modele 2D osteoporotice corespunzătoare zonei proximale a osului femural uman. Modelele 2D osteoporotice respectă indicele Singh de evoluţie a osteoporozei şi sunt realizate din răşină epoxidică şi cauciuc siliconic. Modelele plane sunt solicitate mecanic prin intermediul unei maşini de încercat universale Instron astfel încât să corespundă unui sprijin unipodal. Se utilizează metode de investigare experimentale (metoda corelaţiei digitale a imaginii) şi numerice (metoda elementului finit). Rezultatele obţinute prin analiza comparativă a modelelor osteoporotice 2D evidenţiază migraţia zonei maxim solicitate dinspre zona trohanterului mic (corespunzătoare unei structuri trabeculare şi corticale sănătose) spre zona fibrei inferioare a colului femural (corespunzătoare unei structuri trabeculare şi corticale osteoporotice). Analiza stării de tensiuni şi deformaţii din modelele 2D osteoporotice, prin care se evidenţiază secţiunile maxim solicitate mecanic, au o mare relevanţă în condiţiile în care incidenţa fracturilor cauzate de osteoporoză este extrem de ridicată.*

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