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# *Evaluation of the combined bending and compression stress field in a human proximal femur*

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*ABSTRACT*

Regarding the mechanical behavior of the femur, there is an interest to find out if it works under bending or compression. Accordingly, the stress field; over five cross sections along the femur stem, were studied, following a numerical approach with the Finite Element Method, which had been validated in a previous paper with reflective photoelasticity. For this purpose, loads were applied on the femur head as in Taylor's paper. The numerical model considers the mechanical properties of the cortical and trabecular tissues. The results have shown that the femur stem is under asymmetric bending and the compression.

*Key Words:*
Proximal femora, Compression, Bending, Numerical stress analysis.

*RESUMEN*

Con respecto al comportamiento mecánico del fémur, es interesante saber si éste trabaja bajo flexión o compresión. Por este motivo se estudiaron cinco secciones planares a lo largo del fémur usando el método numérico de los elementos finitos, el cual ha sido previamente validado en publicaciones sobre fotoelasticidad reflectiva. Para este propósito, se aplicaron cargas a la cabeza del fémur como en la publicación de Taylor. El modelo numérico considera las propiedades mecánicas de los tejidos cortical y trabecular. Los resultados muestran que el fémur se encuentra bajo compresión y flexión asimétricas.

*Palabras clave:*
Femora proximal, compresión, flexión, análisis numérico de estrés.

## *INTRODUCTION*

One of the topics that has attracted attention is the exact evaluation of the mechanical behavior of the human femur. Several studies have been done, in order to establish if the femur is under compression or bending. For this purpose, experimental stress analysis has been applied, common techniques such as reflection photoelasticity or strain gages have been used. In the first case, the complete surface stress field is obtained, while with the second technique, a single point is analyzed. It is really a complex problem because the mechanical properties of the human femur bone are not isotropic and they vary from person to person. Besides, the femur shape is an irregular one; therefore, its cross section is asymmetric. The exact evaluation of the resultant stress field is not an easy task. Nowadays, it is possible to evaluate the surface stresses with an experimental technique at the femur shaft. With this information it is possible to calibrate a numerical model and determine the stress distribution on different cross sections.

In a previous paper[1], strain evaluation on a cadaveric proximal femora was done with reflective photoelasticity and the finite element method. Step gradients were observed on the femur head, while on its shaft the strain was cross validated with both techniques.

Recently, Glisson and coworkers[2] have made a careful analysis of the results obtained with strain gages and reflective photoelasticity. They pointed out that depending on the femur geometry, there are some points in which an exact determination of the resultant strain can be done. This is the case of the proximal medial region.

Regarding the results reported on the open literature, Yoshioka et al.[3] commented that it is not possible to compare results of some studies, because it is not clearly established the location of the system of reference that was used. Nonetheless, the use of the longitudinal axis of the diaphysis is suggested as the vertical axis.

In relation with the mechanical behavior of the femur, Taylor and coworkers[4] concluded that the femur is mainly under compression rather than bending. Based on radiological and finite element method.

Actually, the evaluation of the stress and strain field on the surface femur is possible with certain degree of accuracy. Nonetheless, it is not clear how the bending and compression stresses are combined over the whole femur stem. Considering the points mentioned above, the purpose of this communication is the evaluation of the stresses on the cross section of the proximal stem femur. For this purpose, an experimental-numerical approach is followed, which has been validated elsewhere[1]. The obtained results with reflective photoelasticity show that the principal stresses on the surface of the proximal medial region are on line with those obtained with the finite element method. In this work, these results are extended, so as to get a deeper knowledge on the mechanical behavior of the femur, in order to establish the level of compression or bending which is developed.

## NUMERICAL ANALYSIS

In first instance, it was considered that the femur bone has two sort of tissues, namely, trabecular and cortical. Therefore, the head and neck femur have an external cortical layer, which is 1 mm thick. This situation was considered in the development of the Finite Element Model. The remaining upper femoral part is formed with trabecular bone. The transition between to sort of tissues takes place on the upper part of the diaphysis an the rest of the model was considered as cortical bone.

The femur model was developed from tomographic images. For this purpose, slices were taken every 5 mm. The images were digitized and in order to develop the volumetric model 16 keypoints were obtained (Figure 1). With two adjacent slices, a wire model was generated and from this a solid model was obtained. Adjacent solid models were merged until the whole femur model was obtained. Thereafter, the whole model was meshed. The finite element code used was ANSYS 6.1.

Figure 2 shows the model generated. It has to be kept in mind that the vertical axis coincides with the longitudinal axis of the diaphysis. Also, in this

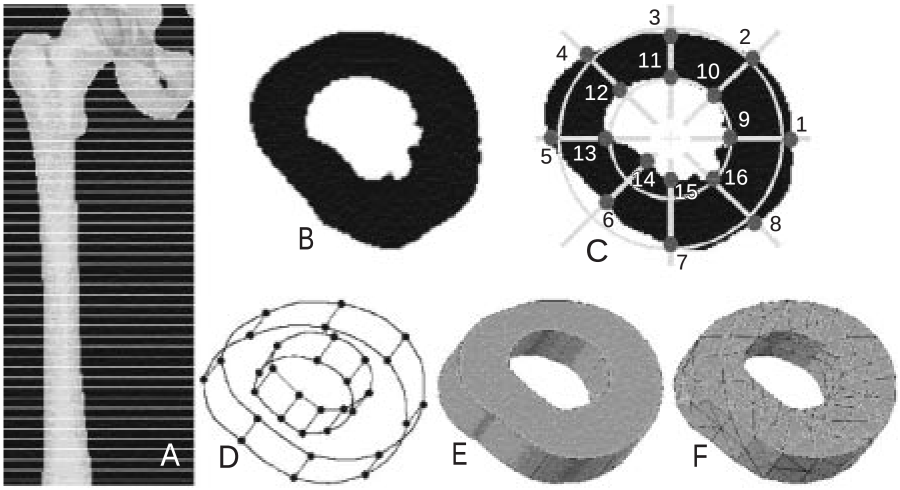

**Figure 1.** Model construction. A) Tomographic study; B) A Tomographic slice, C) 16 Keypoints; D) Wire model; E) Volumes and F) Mesh.

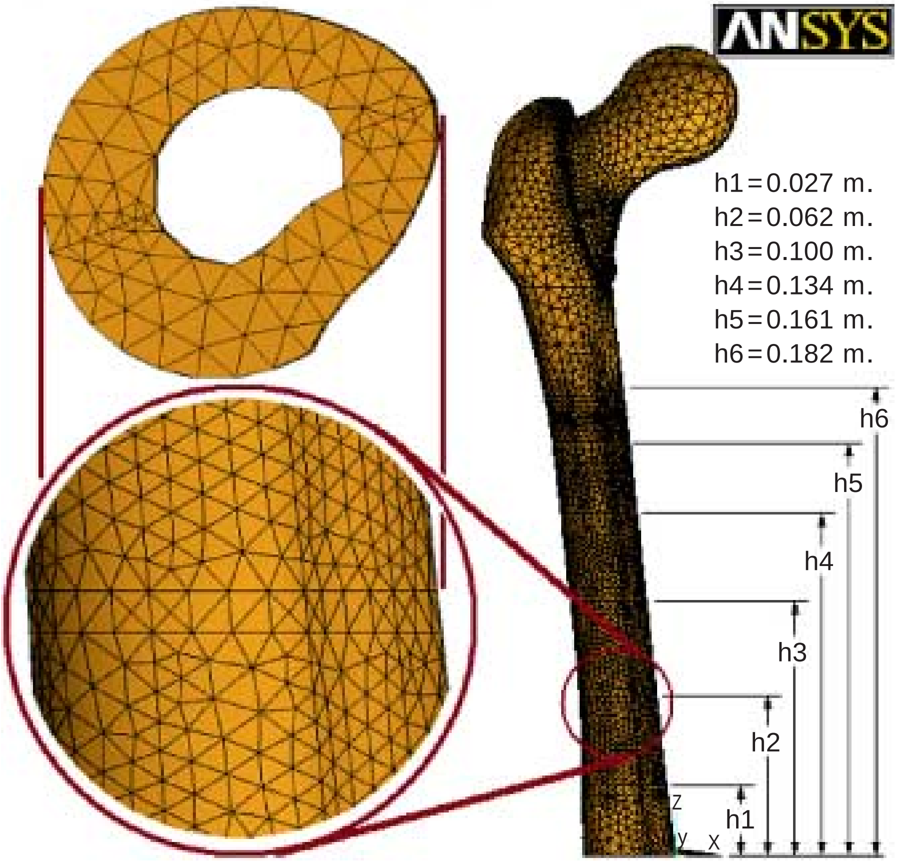

**Figure 2.** Model generated and location of six crosses sections h1, h2, h3, h4, h5, h6 along the femur stem, considered for this work.

figure, details of the mesh of the femur stem and a typical cross section is shown, as well as the location of six sections (h1, h2, h3, h4, h5, h6), on which the stress distribution was determined. The first one h1 is located close to the distal end; it is as well the fixing point, while the last one, h6, is close to the femur head.

This mesh has 140,296 nodes. Accordingly, the trabecular portion was modeled with 93,474 tetrahedric elements of ten nodes, while 3,558 shell elements of four nodes were required for the cortical bone simulation. In order to reproduce the experimental conditions and, as well as establish a comparison, with results reported by other authors, the loads considered by Taylor et al.[4] were applied over the femur head in according with those authors these are the more representative loads over this femur. Besides, the bone was considered as fixed at its bottom (Figure 3). The following summarizing applied loads.

The mechanical properties, in the cortical bone, were considered as transversely isotropic. That is, the modulus of Elasticity along the longitudinal axis is 17 GPa, while in the perpendicular direction, the value of this parameter is 11.5 GPa. In the cortical bone, the modulus of Elasticity is 1 GPa.

**Table 1**. Loads, applied by Taylor et al[4].

| Force | Applied vectorial forces (kN) X | Y | Z | Resultant |
|---|---|---|---|---|
| Joint reaction force | 1.062 | -2.800 | 0.130 | 2.997 |
| Adbuctors | -0.430 | 1.160 | | 1.237 |
| Ilio-tibial tract | | -1.200 | | 1200 |
| Iliopsoas | -.078 | 0.525 | -0.560 | 0.771 |

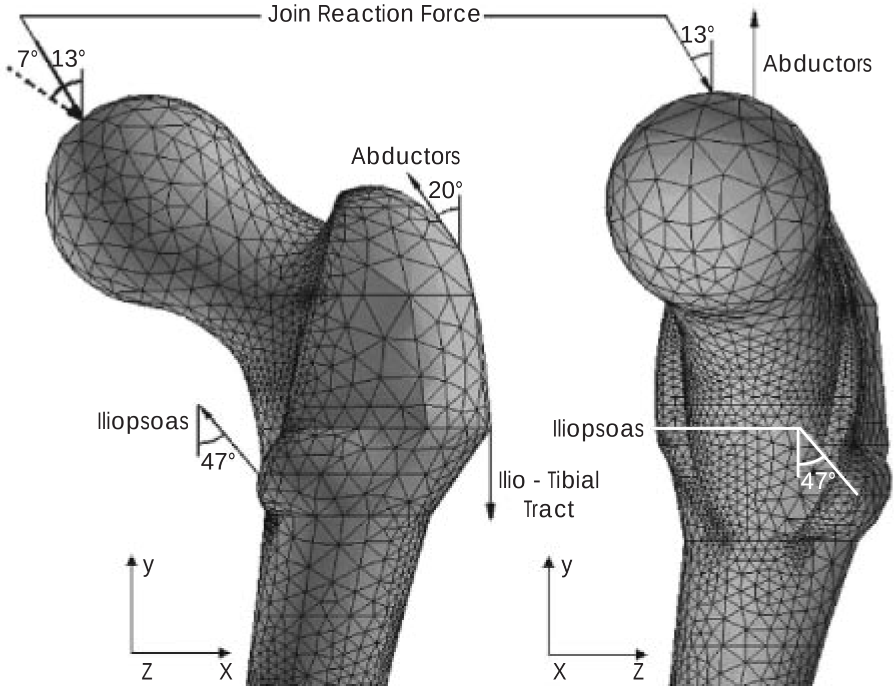

**Figure 3.** Loads used by Taylor (1996).

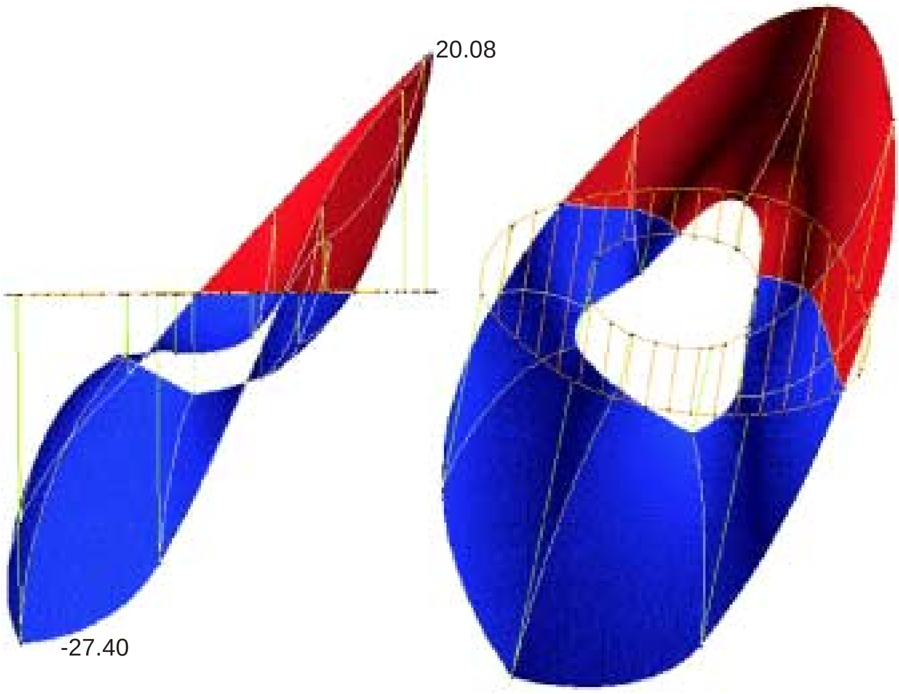

**Figure 4.** Stress field of detailed stress field of cross section h6.

## *OBTAINED RESULTS*

Fracture is a common failure, under this type of loading so, it is important to identify the region on which the maximum principal stresses are developed. On the other hand, compression is associated with the minimum principal stresses. It has to be kept in mind that bending is the combination of both stresses in a single cross section.

The maximum and Minimum Principal Stresses are perpendicular to the femur cross section. As a result, there are two regions, one under tension and the other are compression. The last one is the highest. It can be said that the femur is subjected to bending and compression. This is a common situation along the femur stem (Figure 5). Table 2 summarizes the result stresses over the analyzed sections. Another point, which has to be observed, is the fact that the points of maximum tension and compression stresses are on the opposite sites. However, their position varies in accordance with the geometry at the cross section. This suggest that the femur is under asymmetric bending.

Figure 4 shows a typical result, which corresponds to plane 6. Table 2, summarizes the critical values under the applied load.

These results are in agreement with those observed in[1], in which the isoclinic fringes on the femoral diaphysis tend to be parallel to the femoral axis and, at the same time, the principal strain angle is practically constant. Also, this is with the work reported by Mc. Namara[5] and Brekelmans and cocoworkers[6]. In the first case, they applied an experimental method using strain gauges, and showed that the principal strain directions are very close to this axis. In the second case, the stress trajectories are along the femur stem.

## DISCUSSION OF THE RESULTS

The femur shape is an irregular one. In accordance with results reported in open literature, for example[2], the region on which the stress can be experimentally evaluated with a greater level of accuracy is over the femur stem. In the case of the reported work in this paper, the starting point comes from the results obtained with reflective photoelasticity on this region[1], and from this, the internal stress field was evaluated.

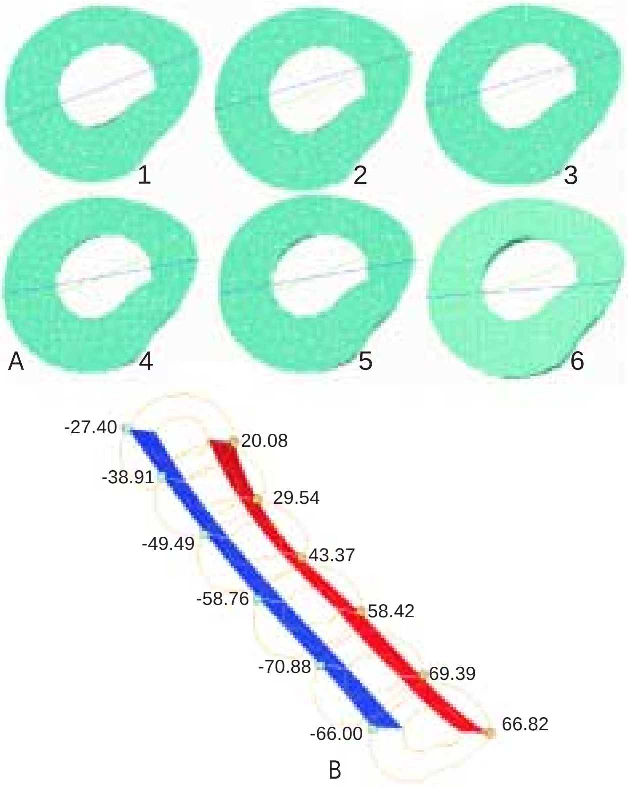

**Figure 5.** Maximum and minimum principal stresses on the cross sections studied. A) Localization of the maximum and minimum principal stresses; B) Variation of the maximum and minimum principal stresses along the femur stem.

The femur cross section of the stem is not symmetric one and it is not constant along the femur stem and there is a slight variation of inertia moment. In consequence, this is a typical asymmetric bending problem. This explains the fact that there is the stress increase in the first two planes and, then, there is a decrease. This is in line with the femur gradual geometric variation.

**Table 2**. Maximum and principal stresses at planes of interest.

| Plane location from distal end | Maximum principal stress | Minimum principal stress |
|---|---|---|
| (m) | (MPa) | (MPa) |
| 0.027 | 66.82 | -66.00 |
| 0.062 | 69.39 | -70.88 |
| 0.100 | 58.42 | -58.76 |
| 0.134 | 43.37 | -49.49 |
| 0.161 | 29.54 | -38.91 |
| 0.182 | 20.08 | -27.40 |

In the first five cross sections the extreme value of the stresses were close to the end of axe four, in such away that the external part is under tension, while at the inside is compression. This situation is slightly changed on the sixth plane, the points of extreme stress values are around the ends of axis one. This plane is closed to an irregular cross section of the femur head, as a result a disturbance on the depending field is generated.

## CONCLUSIONS

The numerical model discussed in this paper consists in the four more representative loads, which are developed over the femur. Moreover, the geometry of the cross section varies along the femur stem. As a result, the resultant bending and compression field alights rotate. The most critical stresses are at the bottom.

## *ACKNOWLEDGEMENTS*

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