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A qualitative stress analysis of a cross section of the trabecular bone tissue of the femoral head by photoelasticity

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ABSTRACT

In this work a qualitative analysis of the stress distribution of the femoral head of a human femur by photoelasticity is presented. A model of the cross section was obtained by plaster casting, carefully maintaining the internal architecture of the porous bone. Here punctual loading was applied aimed to evaluate the trabecular behavior. The fringe patterns observed in the porous bone model showed that the maximum stress concentration is shifted from the surface to the interior of the bone, allowing the damping of external forces and diffused them towards the interior of the bone tissue, thus reducing the contact stresses at the surface of the femoral head joint. These results showed that solid models will tend to mislead the stress behavior within the bone.

Key Words:
Stress, Trabecular bone, Photoelasticity.

RESUMEN

En este trabajo se presenta el análisis cualitativo por fotoelasticidad de la distribución de esfuerzos de la cabeza femoral de un fémur humano. Aquí se obtuvo por moldeo en plástico una sección transversal del hueso poroso, manteniendo cuidadosamente la arquitectura interna. Para evaluar el comportamiento trabecular, aquí se utilizó una carga puntual. Las franjas isocromáticas que se observan el modelo de hueso poroso muestran que la máxima concentración de esfuerzos se desplaza de la superficie al interior del hueso, lo que permite el amortiguamiento de las fuerzas externas y las difunde hacia el interior del tejido del hueso. Esta condición reduce los esfuerzos de contacto en la superficie de la unión de la cabeza femoral. Estos resultados muestran que los modelos sólidos tienden a sobreevaluar el comportamiento de los esfuerzos en el hueso humano.

Palabras clave:
Hueso, tejido trabecular, fotoelasticidad.

INTRODUCTION

A first reference commonly cited in the study of the long bones, is that of Wolff in 1892[1]. In his work, basically through the observation of trabecular orientation, he established that trabecular morphology matches the stress trajectories. Almost 100 years later, Huiskes[2] addresses the 2 different paradigms of Wolff and Roux concerning the relationship between bone architecture and its mechanical function. He confirmed through Finite Element Analysis (FEA) that Wolff's trajectorial hypothesis holds, and that the orientations of the trabecular architecture corresponds with those of the principal stresses, and hence, with the stress trajectories as determined in models with continuous materials. The availability of numerical techniques, in particular FEA, and modern computers have given the opportunity to explore the mechanical properties of bone considering both the density distribution, architecture[2-4], and mechanical behavior under external forces, for example those caused by rising a chair[5] or knee flexion[6]. These works, amongst others, have constituted the basis for the development of models oriented to understand the state of stresses in bones.

As already mentioned, FEA has become an important tool for bone and bone tissue modeling. A first step in FEA is to obtain bone geometry and architecture by computerized tomography or magnetic resonance imaging. Then, a model can be evaluated under specific considerations, such as the material being isotropic[7], or a composite material aimed to represent the cortical or trabecular bone tissue[8]. However, numerical techniques by themselves may not be trustworthy without being properly accompanied by experimental mechanical properties and a numerical validated algorithm[9].

Experimental techniques for stress analysis have always being useful to explain and measure stress behavior. Among them, one can find those developed using pressure sensible films to evaluate contact stresses[10]. Fessler[11], on the other hand, used photoelastic techniques to study the stress behavior in solid models representing the central frontal plane of a normal hip joint. The prime objective of Fessler's investigation was to study the load distribution on the acetabular roof, that is, to determine the compressive stress perpendicular to that surface.

In the particular case of the knee, Papachristou[12] investigated the stress-strain situation of the knee joints in models made from 1 cm thick Araldite plates, thus ignoring the internal architecture of the porous bone. He found out that the application of a longitudinal force on a normal knee joint, in full extension, results in symmetrical arrangement of trajectories in the condyles. Also, that loading of the leg in varus or valgus produces shifting of stresses towards the inclination side. Similar work was carried by Antonescu[13].

The stress analysis by means of homogenous and isotropic models has been questioned from the beginning. The considerations that the investigators make to support their findings, are not sufficient for the total understanding of the mechanical properties of the bone. Between the most recent and reliable works one can find the technique of micro photoelasticity, which consists of the reproduction of the structure of the trabecular bone with photoelastic models whose objective is to understand structural geometries and the transmission of load[14]. In this work, a qualitative photoelastic study is made of the stress behavior of a distal femur trabecular bone subjected to loads a different angles.

Model casting

The model was casted from a section of the proximal femur of a healthy adult woman. A cross sec-

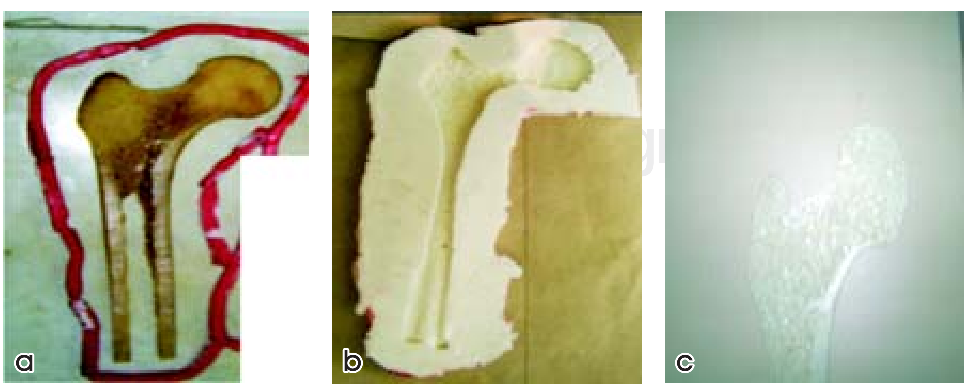

Figure 1. Plaster casting molding. a) Histological sample; b) Silicon mold; c) photoelastic model.

tion 1 mm thick, at the sagital plane of proximal femur was first obtained, as the one shown in Figure 1(a). The porous tissue was the cleaned to free it form any traces by chemical treatments with detergents. Once the cross section was cleaned, the mold is obtained using silicon a shown in Figure 1(b). The silicon was prepared and poured to fill the trabecular cavities and then let to cure itself for two days. Then, the mold was carefully separated from the bone and an epoxy resin type GY 6010 and a HR curing agent, was then casted to obtain the photoelastic model, which included the trabecular architecture of the bone's as shown in Figure 1(c).

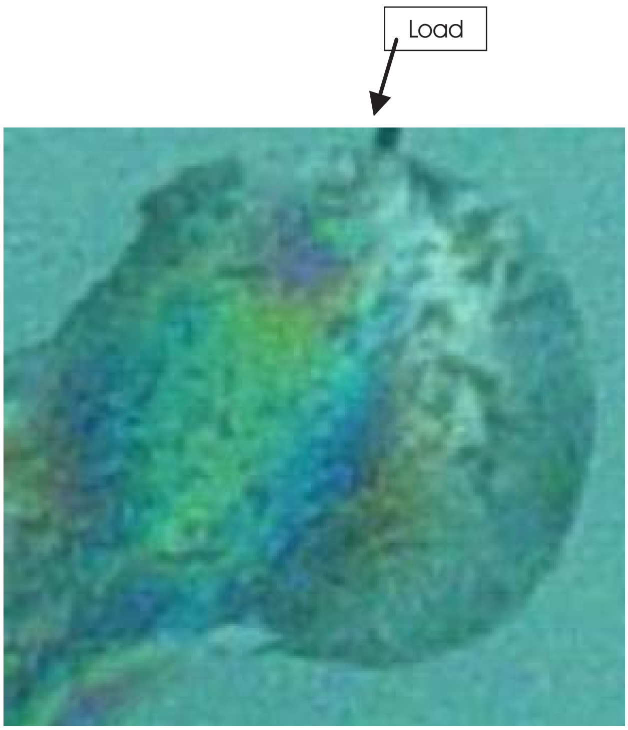

Figure 2. Isochromatic fringes top.

RESULTS

The experimental test was carried out with the prime objective of analyzing the trabecular effect on the stress distribution, thus no load device was constructed, but punctual loads were applied at different angles. Here the images presented will be recognized as (a) Top (b) Middle and (c) Bottom. A photograph of the isochromatic fringes obtained when loading the photoelastic model is shown in Figure 2. Although no calibration of the relation of fringes color to load and stresses was made, still the change of color from white to red can be linked to no load to high load respectively. It can be noted from Figure 2, that there is not an exclusive zone where a predominant color could be distinguish, differentiating this results from those obtained in solid models11. This, could be attributed to: (1) light contamination or (2) A probable odd stress distribution caused by the trabecular tissue.

A Finite element model was constructed of a small section of trabecular tissue, and subjected to a uniform compression load, with the sole purpose of analyzing the stress distribution in the trabecular tissue. In Figure 3 are shown the results of the FEA model. Here, the Von Misses stresses are colored from minimum with blue to maximum in red. It can be noted from Figure 3, that an odd distribution of stresses within the sample are found and that low and high stresses can be presented in the same region. Regarding light contamination, the images obtained were characterized and all the noise ex-

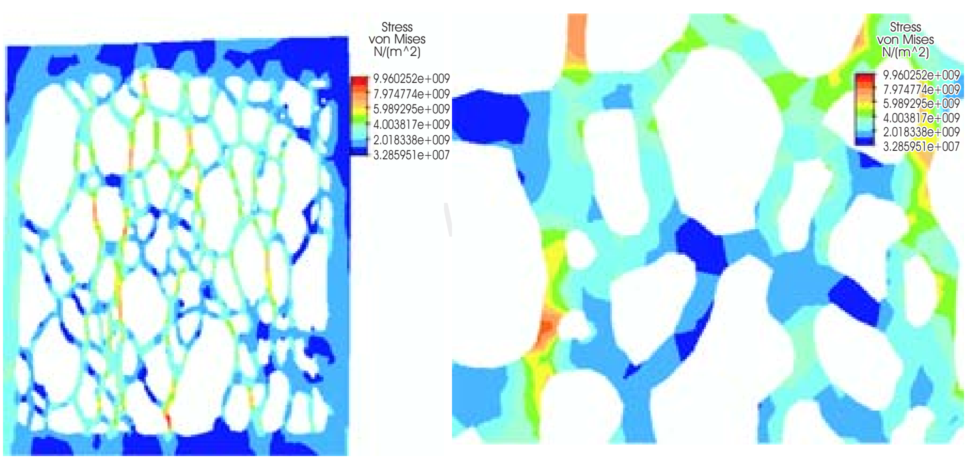

Figure 3. A trabecular section at compression loading.

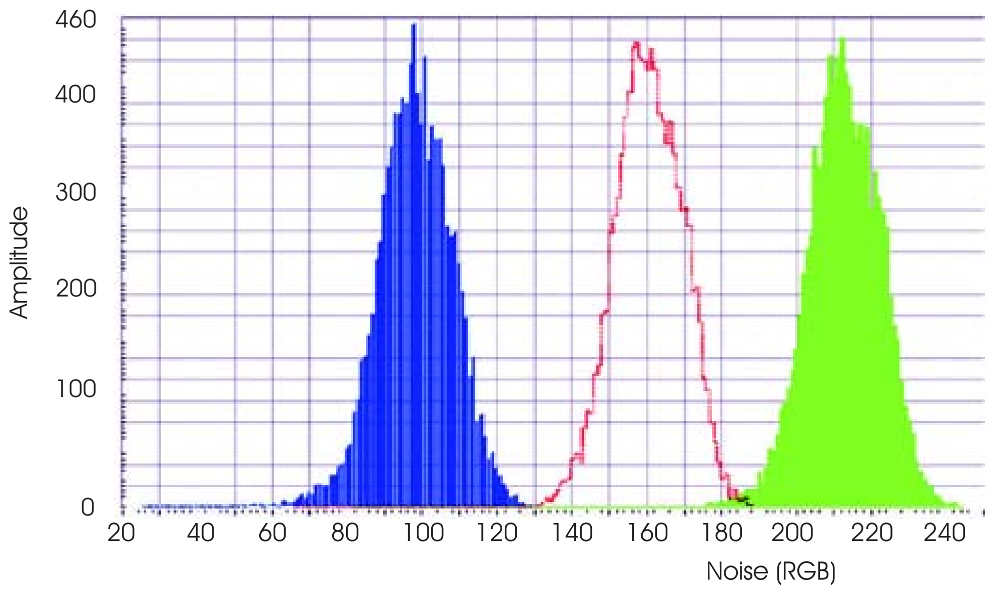

Figure 4. Noise characterization.

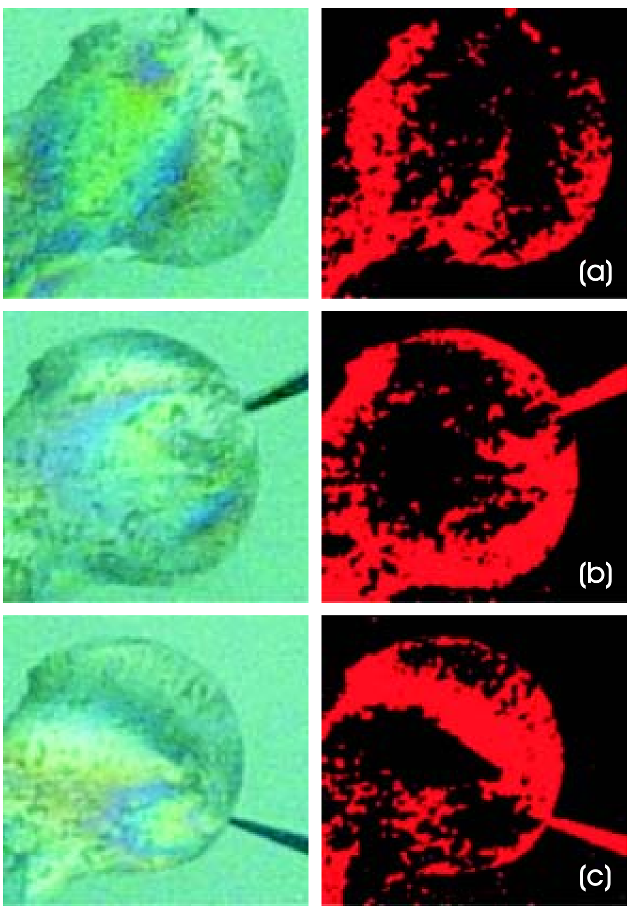

Figure 5. Photograph of fringe patterns and its filtered image: (a) Top; (b) Middle and (c) Bottom.

tracted from each of them. Figure 4 shows the noise characterization from the images, once this was obtained the signal/ratio evaluated and then subtracted from each image, thus obtaining a nearly clean image.

With the characterization process completed, the fringes can be readily obtained. For the present work, the highest stresses concentrations are only considered. These can be located within the red region. In Figure 5 are shown the photographs and fringe patters for maximum stress for the cases of (a) Top; (b) Middle and (c) Bottom, which correspond to the initial, one quarter and half march cycle. Here an arrow was introduced to show the position of the contact between the model and the rolling table. An interesting feature can be noted from the three examples, this is that the maximum stress concentration, in red, moves from the surface to the interior of the model thus reducing the surface stress concentration, condition that differs from the common results obtained from solid models[11].

The former observation can be explained if the bone tissue could be considered as a granular composite material. As the surface is loaded, the stresses are transmitted to the interior of the composite material where the particles embedded in the body of the material received most of the load, thus changing its stiffness and adding some damping to the process[17,18].

CONCLUSIONS

A qualitative study of a cross section of the trabecular bone tissue of a femoral head by photoelasticity was carried out. Two important features can be argued from the results: (1) The trabecular architecture causes that no define fringes could be found within the images and (2) The fringe patterns observed in the porous bone model showed that the maximum stress concentration is shifted from the surface to the interior of the bone, allowing the damping of external forces and diffused them towards the interior of the bone tissue, thus reducing the contact stresses at the surface of the knee joint, behavior that is similar to that exerted by granular composite materials. Thus a solid model as commonly employed in stress calculation of bones, can be misleading.

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