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THE DEVELOPMENT OF A TWO-DIMENSIONAL STRESS-OPTICAL MODEL OF THE OS COXAE

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On the basis of a previous analysis of the internal stress pattern of the os coxae two types of two-dimensional models for stress-optical analysis are developed and the experimental set-up and procedure are described. The models may be used in an analysis of the principal stress pattern changes following the insertion of various types of hip prostheses.

Key words: pelvic bones; stress, mechanical

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The loosening of the acetabular component of total hip replacement prostheses is an increasing problem in orthopaedic surgery. It is now accepted that many of these loosenings are caused by mechanical problems, but so far little is known of the actual mode of fixation. The implants are foreign bodies with different mechanical properties and behaviour and they may be expected to cause changes in the stress patterns in the pelvis or at least around the acetabulum.

It is the theory of this author that changes in the stress patterns around the acetabular component of a hip replacement may lead to remodelling of the bone and therefore to loosening. In works on the mechanical behaviour of acrylic cement (Holm 1980b, c) it was shown that the contracting cement is capable of developing considerable forces during fixation in the anchoring holes. To investigate this problem further a two dimensional model of the os coxae was developed.

MATERIAL AND METHODS

A short description of the stress-optical method will be given. For details the reader is referred to textbooks on the subject (Föppl & Mönch 1972, Heywood 1969, Wolf 1976). The stress-optical method is based on the fact that certain plastics become birefringent when subjected to mechanical stress. The material may be regarded as consisting of tiny spheres which under stress are deformed into ellipsoids (Figure 1), with different refractive indices along the two axes. The degree of deformation of these (imaginary) spheres will depend on the magnitude of the force applied whereas the orientation of the axes of the ellipsoid will depend on the direction of the force.

This effect is analysed in polarized light. The stressed model is placed between two polarizing filters which are turned so that their directions of polarization are crossed at right angles thus obtaining maximum extinction of light. The filters are coupled so that they maintain this position relative to one another when turned.

When polarized light enters the stressed model it will be refracted according to the stress situation in each particular area of the model. The angle of the light will be altered and it will therefore pass through the second filter. The model will thus appear luminous on a dark background.

Isoclinics: In certain areas of the model the direction of the principal stresses will coincide with the plane of polarization of the incident light. In these areas there will be no changes in the angle of the light as it passes through the model and there will be total extinction of light emerging from these areas which are called isoclinics.

The isoclinics are seen as dark bands in the model and as the filters are turned, and the plane of polariza-

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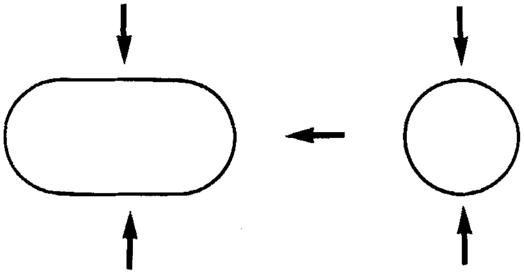

Figure 1. The deformation of a birefringent material causes it to demonstrate different refractive indices which depend on the direction and the magnitude of the stress. The change in the refractive indices is illustrated by the change in the sphere, having equal diameters, into an ellipsoid with the major and minor diameters indicating the directions of the two principal stresses.

tion coincides with the direction of the principal stresses in new areas, the dark bands will be seen to move across the surface of the model. By proper registration of the lines and the corresponding direction of the polarization plane the orientation of the principal stresses throughout the model may be described. The isoclinics thus indicate the direction of the stress and are independent of the magnitude of the stress. By means of the isoclinics the stress trajectories may be drawn.

Isochromatics: When white light is used to illuminate the loaded model a number of coloured lines will appear, the so-called isochromatics. Areas of the same colour indicate areas where the difference between the two refractive indices of the birefringent material is the same. These lines or fringes do not change position in the model when the polarizing filters are turned. Their colour and their number are dependent on the magnitude but not on the direction of the stress.

Singular points: In certain areas of a stressed body a situation may exist in which the principal stresses have equal value in all directions; the stress is "hydraulic". This value may be zero or it may be positive. These points are called singular points.

Singular points are basically divided into two categories: attractive and repulsive points. In the attractive singular point the stress trajectories curve sharply around the point whereas in repulsive points they bend away from it. Singular points may stretch into singular lines or areas. In repulsive singular points that are found at a surface the stress will always be nil (Wolf 1976) (Figure 2).

Stress trajectories are imaginary lines that indicate the direction of the principal stresses, tension and compression. They must by definition always cross each other at right angles. The density of the lines drawn in any particular drawing shown in this article has no bearing on the magnitude of the stress but only on its direction.

Apparatus

The equipment used was a simple polariscope consisting of a light source which could give diffuse white or monochromatic Na-light and two polarization filters mounted in revolving frames and coupled so that they would maintain their relative position.

The loading machine was designed specifically for the purpose of testing models of the acetabulum during varying conditions as to direction and magnitude of loading. It consisted of a central mounting frame where the model was mounted between supporting plates of acrylic.

Around the frame was placed a ring with two pulleys attached to the upper half over which the loading cables ran. The ring may be turned by means of a small electric motor so that the direction of loading could be altered at will without complicated rearrangements of the set-up. The ring was controlled by an alternating switch in order to prevent accidental damage to the pulleys. The applied load was balanced to avoid torsion by letting the loading wire go through a pulley to which the weights were attached (Figure 3). Outside this ring was placed a frame for the application of stationary loads such as the load on the trochanter area.

Photographic procedure

In the present experiment the stress trajectories were recorded directly with a photographic technique which avoided the cumbersome graphic methods usually employed. The procedure used was based on the method developed by Kummer (1956) and modified by Hochgesand & Gärtner (1970). The model was mounted with the suitable load between the crossed polarizing filters. The isoclinics were photographed

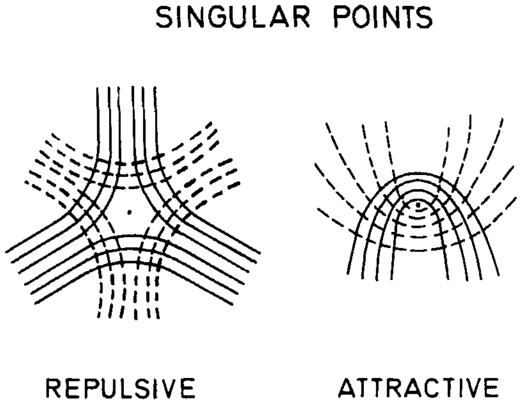

Figure 2. The stress trajectories of repulsive and attractive singular points.

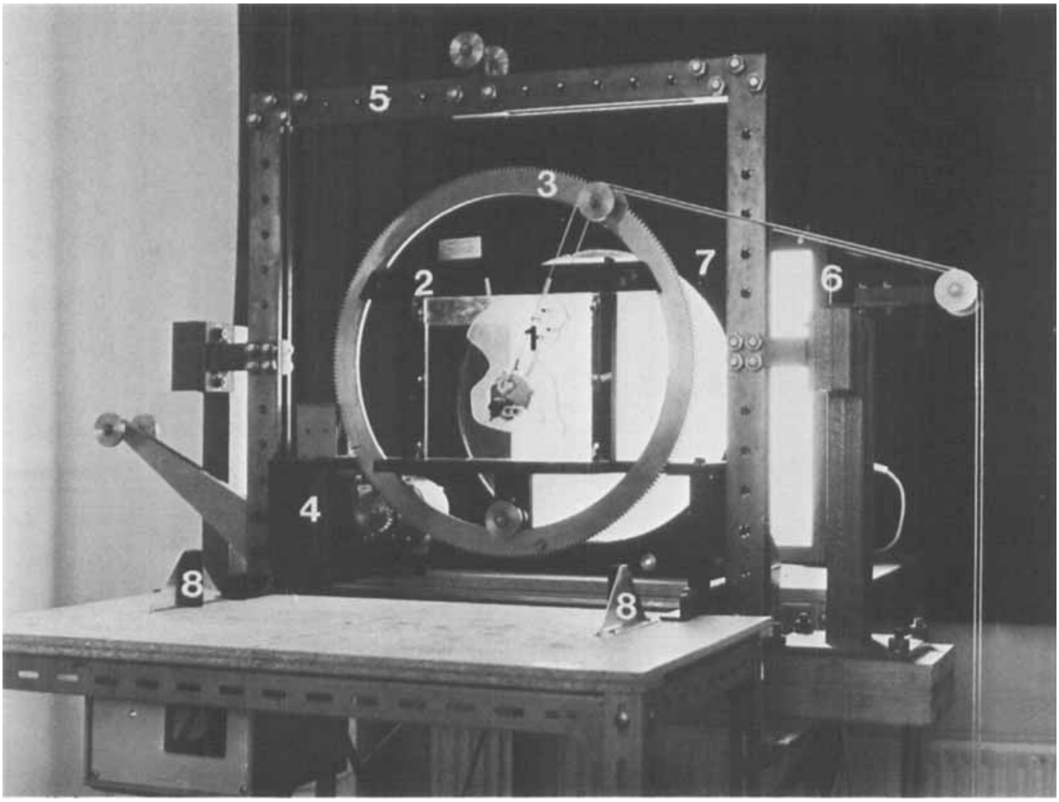

Figure 3. Apparatus for stress-optical analysis 1. The model; 2. Mounting frame; 3. Turnable ring with pulleys for loading at different angles; 4. Motor and alternating switch; 5. Frame for the application of stationary loads; 6. Light source; 7. Polarizer; 8. Holders for analyzer (removed).

with a 300 mm tele-lens from 4 metres distance. A mesh with 2 mm interspaces (Curtain material Gardisette®) was mounted on the outside of the polarizer with the directions of the threads corresponding to the direction of polarization. Nine successive pictures were taken with the polarizing filters turned 10° for each picture. The mesh of course turned with the polarizer so that the angle of the plane of polarization would be registered simultaneously. The nine negatives were then copied on the same piece of paper. As the dark isoclinics would be light in the negative with the rest of the model being black, the copy would only be exposed corresponding to the isoclinic. This means that from each of the nine negatives only the isoclinic belonging to that particular negative would register on the copy together with the corresponding area of the mesh. Thus a cumulation of the isoclinics was obtained as a picture showing the black mesh on a white background, the mesh having in each area an orientation identical with the planes of the principal stresses (Figure 5).

When the mesh was mounted on the polarizer it came out in the prints with a coarse structure with too large a distance between the lines to show finer details such as singular points. This method was therefore only used for initial orientation purposes.

For finer detail the method of Kummer (1966) was used in which the mesh was photographed nine times in a suitable size and turned the same 10° for each picture as the pictures of the isoclinics. The two sets of negatives were taped together and copied simultaneously. The final picture would appear in the same manner as described above, but with much finer detail. The alignment of the nine pictures on the same piece of paper was achieved by placing the paper in a copying frame. A minimum of three characteristic points, e.g. corners or the crossing of loading wires, were marked on the paper from the projection of the first negative. The marks were then adjusted to the projected image of the next negative by moving the frame under red light.

The camera used was a Nikon 35 mm camera with a 50–300 mm zoom-tele lens. This facilitated close-ups when needed. The film used was Agfa-Ortho-25 professional, which is a very fine grain graphic film. The exposure time for the nine pictures was 10 seconds, f/8. Each series of pictures was started with a marking frame exposed at 0.25 seconds, f/8.

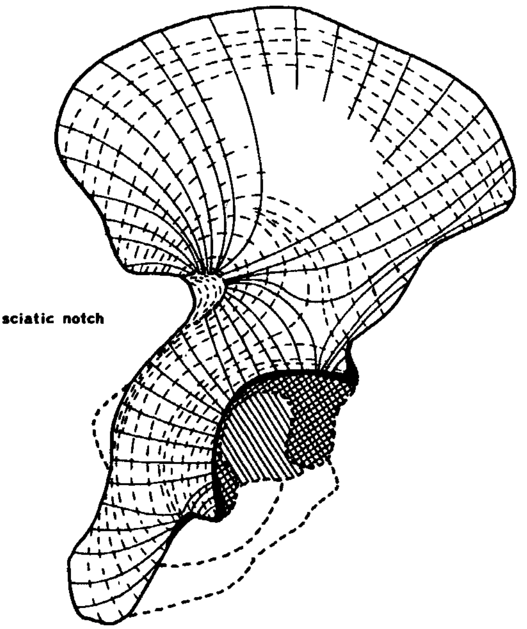

Figure 4a. Stress trajectories of the os coxae derived from the trabecular pattern in a section of 45° to the frontal plane.

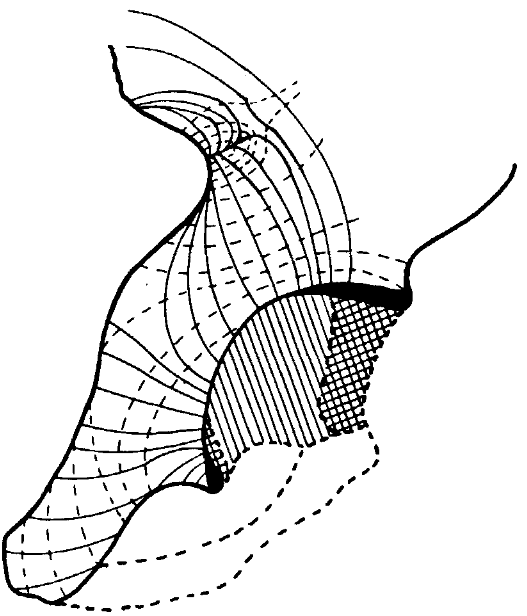

Figure 4b. Stress trajectories of the os coxae derived from a section 0.5 cm deeper than the section shown in Figure 4a.

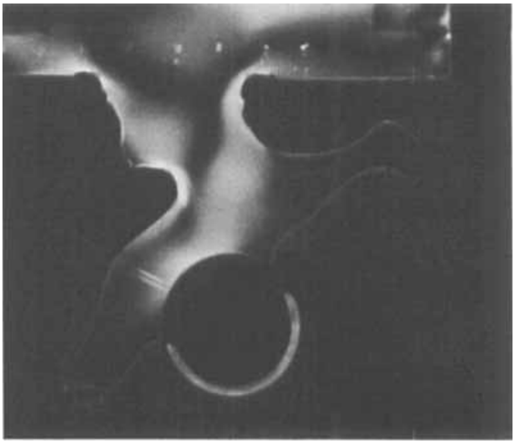

Figure 5. The first attempt at a two-dimensional model of the os coxae. By copying nine consecutive negatives on the same paper the stress trajectories are demonstrated directly. The model is loaded in flexion.

The film was developed in Neutol® for 4 minutes and the copying ensued on medium or hard paper.

The final analysis of the pictures was done by tracing the principal lines of the mesh on transparent paper. From these tracings it was easy to make representative drawings of the stress trajectories as the mode of stressing the model was known from the set-up.

The drawings were made merely for the sake of clarity of illustrations and because it was easier to evaluate the flow of the isoclinics around isotropic points in this way.

The models

Ten mm thick plates of acrylic (Plexiglas®) or Epoxy (Araldit B®) were used as material for the models. Acrylic has a relatively low stress-optical sensitivity and can not produce fringe orders higher than one. For this reason the material is well suited for the examination of isoclinics in the presence of high stresses as disturbing isochromatics hardly appear and may be eliminated through proper exposure of the film and during the ensuing copying. On the other hand it may be difficult to demonstrate the isoclinics in areas with low stresses using acrylic plates. Epoxy is highly optically sensitive and shows distinct isoclinics even at very low stresses. The draw-back of this material is that it has a strong tendency to show time-edge effects due to the absorption of moisture, which will render the model useless after a few weeks. The high sensitivity makes it possible to evaluate the whole of the model, but there may be considerable interference from isochromatics which can not be removed during the photographic procedure.

The models were made by hand. The easiest procedure which did not generate stresses along the edges

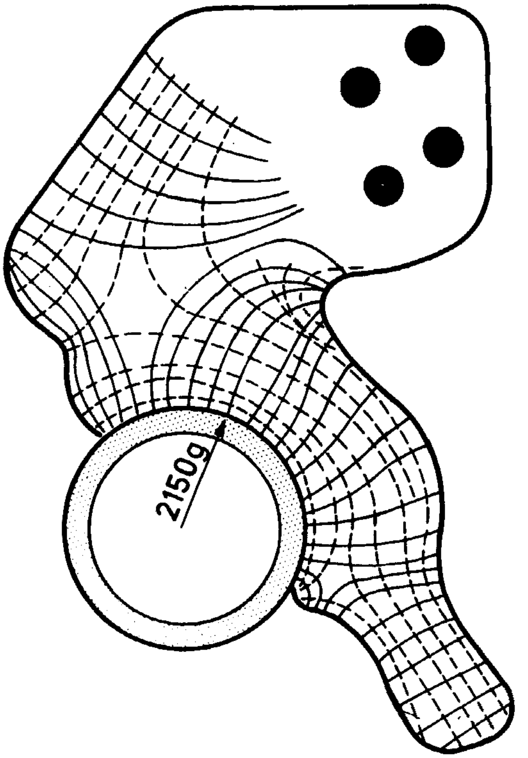

Figure 6a. The second model of the os coxae loaded in the standing position. The applied load and its direction are indicated.

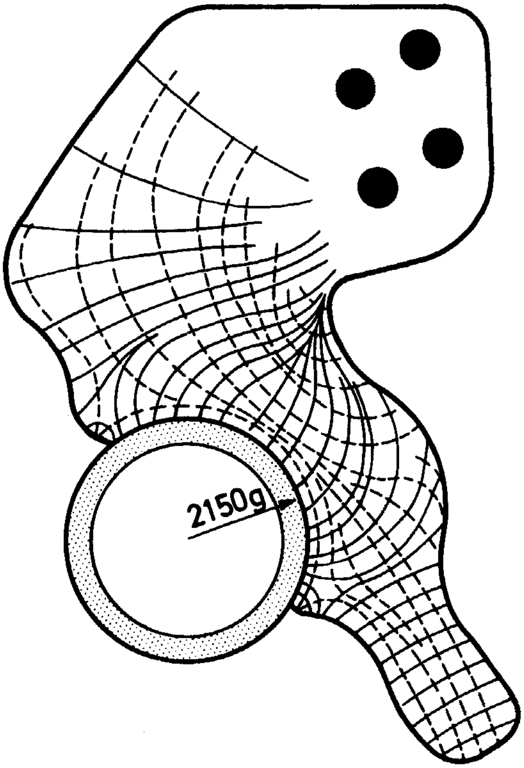

Figure 6b. The second model of the os coxae loaded in flexion.

was sawing either with a band saw or by hand with a jig-saw. The edges of the models were filed smooth and the fit to the loading disc was perfected by hand. Working the epoxy by milling had a strong tendency to generate stresses along the edges which it was difficult and sometimes impossible to anneal out of the model.

Annealing was done by heating the models in an oven to 130° Centigrade and then cooling them at a rate of 3° per hour to room temperature. The models were placed on a glass plate lubricated with talcum or mineral oil during the annealing process.

Residual stresses in the models were either removed entirely in this way or at least diminished to such an extent that they were easily overridden by applied loads.

Any model that could not for any reason be properly annealed or which showed a significant time-edge effect was discarded.

Suspension of the models: The first primitive model was suspended in the apparatus by a wide flange at the top. The flange was squeezed between the stanchions of the apparatus with light pressure (Figure 5). In the later models where the point of fixation was chosen to be in the area representing the sacroiliac joint the method of suspension was altered. The models were fastened to the stabilizing plates with four 5 mm bolts passing through both plates (Figure 6). With this mode of fixation certain interference might be expected as the stabilizing plates were put under stress and therefore might show stress patterns – isoclinics – that might interfere with the model.

However, disturbing isoclinics from the plates were only observed around the suspension area itself. This area was excluded from the final evaluation.

Loading of the models: To imitate the femoral head and the articular cartilage at steel disc with a diameter of 54 mm was used. Around this was cast a rubber ring of Adiprene L 42 synthetic rubber (DuPont) as the cartilage of both articular surfaces (E-modulus = 1000 N/cm^2) (Figure 5). The soft rubber gave a very even distribution of force, but a fairly exact fit was nevertheless necessary in order to avoid unwanted stress concentrations. Because of problems of ageing of the synthetic rubber this was later exchanged for silicone rubber of the commercially available sealing type. The loads used on the acetabular surface were the minimal loads necessary to produce clear isoclinics. The load used in the epoxy models varied from about 2 kg to about 4 kg. In the acrylic models a load of 20 kg was necessary to produce isoclinics. The exact load is not critical because the isoclinics are independent of the magnitude of the load and only depend on the direction in which it is applied.

The load used is marked in each case on the illustration. All models were first examined in the polariscope to check for the absence of stresses in the material. In the epoxy models it was difficult to obtain a complete absence of isoclinics even after annealing, but the stresses were very small and were easily overridden by the applied loads. Any models where this was not the case or where any important time-edge effect had developed were rejected. Models made of acrylic did not demonstrate such problems.

RESULTS

The purpose of these experiments was to make a two-dimensional stress-optical model in which the stress patterns of the bone could be reproduced. The examination of the trabecular structure revealed that the most complete and characteristic trabecular pattern was found in a near vertical section through the acetabular joint surface parallel to the plane of the os ilei, i.e. at an angle of about 45° to the frontal plane. This section was therefore used as a starting point for the development of the model (Holm 1980a). Figure 4a and b show the stress trajectories of this section. In the following, the anatomical names will be used also to describe the corresponding parts of the models.

Experiments with the preliminary flanged model showed that a direct tracing of the contour of the sectioned bone gave too primitive a model as too much of the bone was not represented.

The next model examined had a closer resemblance to the projected contour of the pelvis of the same basic section (Figure 6a and 6b). The ala was projected on to the model plane as a whole and the anchoring point was changed to an area corresponding to the sacroiliac joint. In this model no regard was paid to the os pubis and the inferior rami.

It was found that in the standing position there was a good correlation between the stress patterns and the trabecular pattern. The stress trajectories go from the acetabulum to the posterior aspect of the model and curve around the sciatic notch in a pattern quite similar to the bony pattern represented in Figure 4a. In flexion, however, the pattern is changed so that it is closer to the pattern found in the deeper section of the acetabulum where a repulsive singular point is seen posteriorly – compare Figures 4b and 6b. In both models the gothic arch pattern of the tuber area is not reproduced. The analysis of the trabecular pattern had shown that the tuber ischii must be under the influence of a forward bending stress.

A forward pressure was therefore applied to the tuber in order to imitate the stabilizing effect of the inferior rami and the pubic bone. The exact amount of force necessary to obtain the correct balance had to be found experimentally in each model. Too small a load on the tuber could not balance the posterior bending moment of the acetabular load and too large a load would produce a stress pattern that indicated a forward bending moment in the posterior part of the acetabulum, a pattern which is not found in the bone.

With a load on the tuber as described, it was possible to maintain the trajectorial pattern regardless of the position of the hip (Figure 7a, b, and c).

After this a further adaption of the model was made. The os pubis and the inferior rami were projected out onto the same plane as the rest of the model (Figure 8a and b). This of course is a rather coarse approximation, but as the purpose was to obtain a stabilisation of the tuber similar to that found in the bone, and not to evaluate the pattern in the lower rami, it was thought justified. It was found that the stress pattern which appeared with a single load on the acetabulum resembled closely the one found in the bone (Figure 4b). Also the positions of certain singular points were strikingly similar. The pattern of course showed some difference as the torsional stress present in the pelvis where the pubic bone attaches to the acetabular rim (Holm 1980a) could not be imitated. The pattern here instead showed a bending moment and the gothic arch pattern at the tip of the tuber was deformed into a simple pattern that showed that the forces were simply bending around into the inferior rami. Here on the other hand the correct pattern of tensional stresses in the longitudinal direction was found.

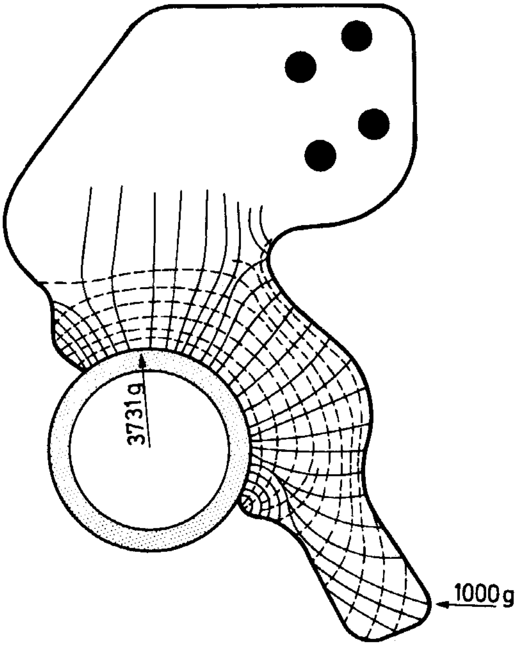

Figure 7a. The stress pattern in the model of the os coxae when a balancing load on the tuber ischii is applied. The joint is loaded in 20° of extension.

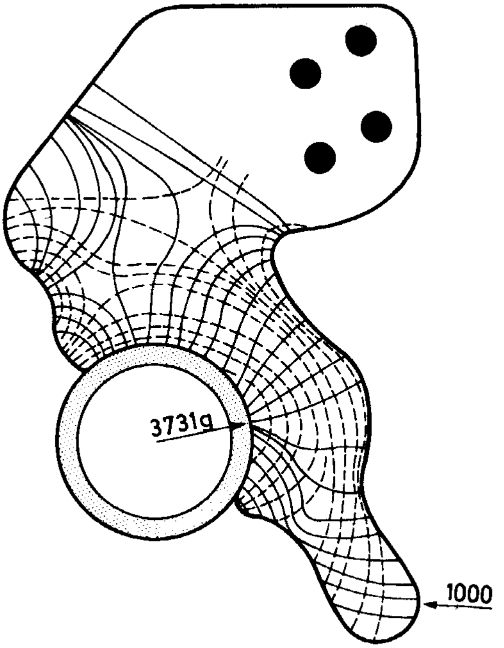

Figure 7c. The same model as Figures 7a and 7b in 70° of flexion. Note that the stress pattern around the acetabulum remains the same in all three situations.

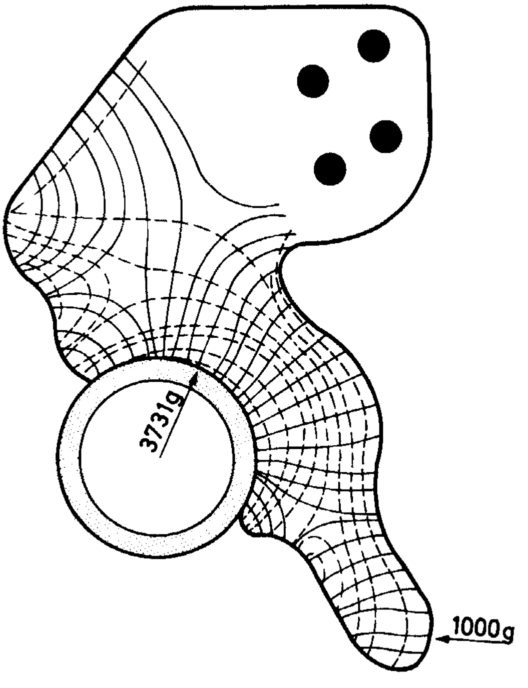

Figure 7b. The same model as Figure 7a loaded in standing.

DISCUSSION

The main objection to applying the stress-optical method to bony structures is that bone is a composite material with a complex inner structure whereas the models are made of homogeneous isotropic material. On the other hand the resemblance between the experimentally obtainable patterns and the trabeculae is so striking that it cannot possibly be coincidental. For this reason the bones may be considered to behave as an orthotropic material, i.e. when they are loaded in a physiological way they behave as an isotropic material. It was therefore felt that if a model of the pelvic bone could be constructed which could reproduce the stress patterns found in the bone it might be used as a basis for further investigations into the changes that might occur with the use of various types of prostheses of the hip joint.

It has been possible through stress-optical experiments to demonstrate relative changes in the magnitude of the stresses. However, the two-dimensional method is not suitable for the evalua-

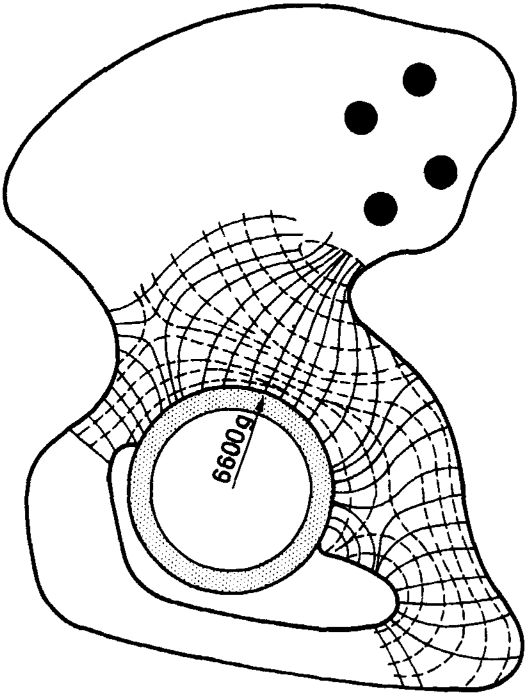

Figure 8a. The third model of the os coxae. Note the similarity between the pattern found here and the pattern in Figure 4b, especially the repulsive singular point at the back of the acetabulum.

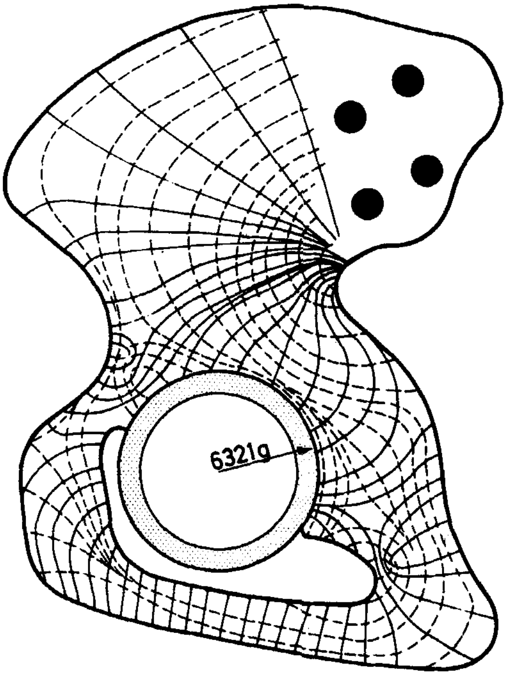

Figure 8b. The stress pattern of the third model of the os coxae when loaded in flexion.

tion of the absolute magnitude of the stresses. For this the models are much too different from the actual three-dimensional bones. In order to calculate actual stresses from a model the frozen stress method must be used on three-dimensional models. This has been done for the proximal end of the femur by Williams (1964).

The analysis of the stress patterns of the pelvic bones is based on the observation by Wolff (1884, 1892) that the trabecular patterns in the bones must be derived from the stress trajectories and that living bone is capable of remodelling according to new stress situations arising from injury or disease. This theory was later criticized (Triepel 1921), but newer experimental evidence has strongly supported it and it is now universally accepted (Kummer 1966, Pauwels 1949, Hert et al. 1972). Previous two-dimensional stress-optical studies on models of bones (Pauwels 1950, Kummer 1956, 1959, 1966) concentrated on bones with relatively simple shapes such as the vertebral bodies, the os calcis and mostly on the head and neck of the femur. Pauwels also investigated the shoulder and elbow joints and used studies of isochromatics to demonstrate the effects of muscle pull. Fessler (1957) has made the only published attempt to study the acetabular area in this fashion. He used a model of a frontal section of the load bearing surface and found that the isoclinic pattern corresponded well with the trabecular pattern.

The pelvic bones have a very complicated shape. It was therefore not obvious how a usable model should look. Other investigators have used a simple tracing of the outline of the bone to be investigated so this method was used as a starting point. This first model proved to be too primitive as major parts of the bone were not represented. The alteration of the point of fixation improved the pattern, but it was not until the forces on the tuber area were imitated that the pattern obtained had a satisfactory likeness to the bone. The balance of the forces is critical and as the complicated shape of the model makes a calculation of the necessary forces very difficult, the balance must be established experimentally for each model, either by varying the load on the tuber or the width of the part which represents the inferior rami. Also the construction of the loading disc is of importance. The E-modulus of the adiprene is about 1000 N/cm^2 whereas the E-modulus of the articular cartilage is about 2000 N/cm^2 (Yamada 1970), but with the loads used in the present experiments this type of rubber was considered adequate and indeed proved to be so in the experiments.

The models developed through the present experiment must be evaluated with caution. They have been capable of reproducing the patterns found in the os coxae and they have shown a number of details that strikingly resemble the bony structure, as well as providing sound evidence in support of the interpretation of the trabecular patterns published previously (Holm 1980a). They contribute significantly to the understanding of the internal stress distribution around the hip.

The models and trajectorial patterns described here can not be expected to demonstrate individual patterns. They are to be seen as demonstrating the principal features of the stress distribution.

In order to evaluate the stress pattern of any specific hip an exact model of this hip would have to be made. Such individual patterns do not seem to be of interest at this stage, but the purpose of the investigation was to gain knowledge of the principal patterns in order to obtain a basis from which further experiments as to prosthetic design may be made. From a stress point of view the ideal prosthesis is one which does not alter the stress pattern of the hip into which it is being inserted and therefore a knowledge of the normal stress pattern is essential.

It must be remembered that the models only demonstrate the direction of the stresses and that they can not be used for the calculation of the actual forces. It is felt that they may be used for further experimental evaluation of stress patterns.

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