

STRAINS AND STRESSES IN THE UPPER FEMUR STUDIED BY THE STRESSCOAT METHOD

By

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Strain and stress analysis in bone may be made by three methods:

1) studies of sections or excised specimens of bone, 2) studies of models of bone, or, 3) studies of whole bone. (Evans 1957).

1) Mathematical analysis of sections, and strain and stress analysis on excised specimens of bone, was the first of these methods to be used. Von Meyer (1867) and Wolf (1870), among others, studied the orientation of the trabeculae in sections of bone. Koch (1920), Grunewald (1920) and other authors made mathematical analyses on transverse sections of bone under assumed conditions of stress. Rauber (1876), Hulsén (1896), and Evans (1951) have made stress and strain analyses using standardized sections of bone. Forsblad (1959) has determined the elastic properties in sections of bone taken from various sites on the human femur.

Due to the complicated architecture of bone and the heterogeneous nature of this biologic material, however, this type of study does not provide an accurate idea of the strain distribution in whole bone.

2) For stress and strain analysis in bone by means of model studies, several techniques have been adopted. Roux (1870) used paraffin-coated rubber models. Under a certain strain, the paraffin cracked, the direction of the cracks indicating the distribution of the stresses. A later method, used, for instance, by Hallerman (1934) and Pauwels (1948), is the photoelastic technique commonly used in industry. With this method, a plastic model is loaded and by transillumination with polarized light, the distribution of the strains can be registered photographically.

The disadvantage of these techniques based on model studies is,

however, that they presuppose a solid construction and a homogeneous material, requirements which are not met by bone.

3) In order to reach an understanding of strain conditions in the whole bone, therefore, the only feasible method appears to be to employ whole bone as the test object. In such studies, what may be measured is, in addition to the applied stress, the strain, i.e. the change in length occurring in the outer surface of the test object under a certain stress. Calculations may be based on Hook's law, which says that the strain is proportional to the causative stress.

A highly accurate method of measuring strain is afforded by the strain gauge technique. With this technique, the change in length is registered electrically by measuring the alteration in the electrical resistance of a metal wire resulting from a change in its length. A condition for obtaining reliable results with this method is, that the strain gauges be applied in the direction of the stresses. The orientation of the stresses cannot be determined from the strain gauges.

By using some kind of strain sensitive lacquer, it is possible to determine the surface strain distribution and the direction of the stresses. Küntschler (1934) used colophonium, applied in melted form. A considerably simpler version of this method, which has become known under the trade name "Stresscoat", was developed by Forester and Ellis (1940). Guardjian and Lissner (1945) were the first to use it in studies of bone. Subsequently, Evans et al. and Frankel have reported on several studies in which this technique was used.

The procedure is as follows. The test object is first sprayed with an aluminum dye, providing a dull, silvery undercoating, and subsequently with a special lacquer. After this has dried for 24 hours, the specimen is ready for testing. When the specimen is loaded, the lacquer cracks. Both tensile and compressive strains produce this result, although in the latter case only when the load is released. The cracks lie at right angles to the direction of the stresses. The number of cracks per unit of length is proportional to the applied stress. The location of the initial cracks indicates where failure will occur if the load is increased to breaking point. By spraying a calibration rod simultaneously with the specimen, and loading it under standardized conditions, it is possible to determine the actual sensitivity of the lacquer, that is, the specific amount of strain required to produce cracks. (Fig. 1). This sensitivity is influenced by temperature and humidity conditions; lacquers of different sensitivity are available to permit adaptation to varying conditions. The cracks are visible under obliquely directed light. (Fig. 2).

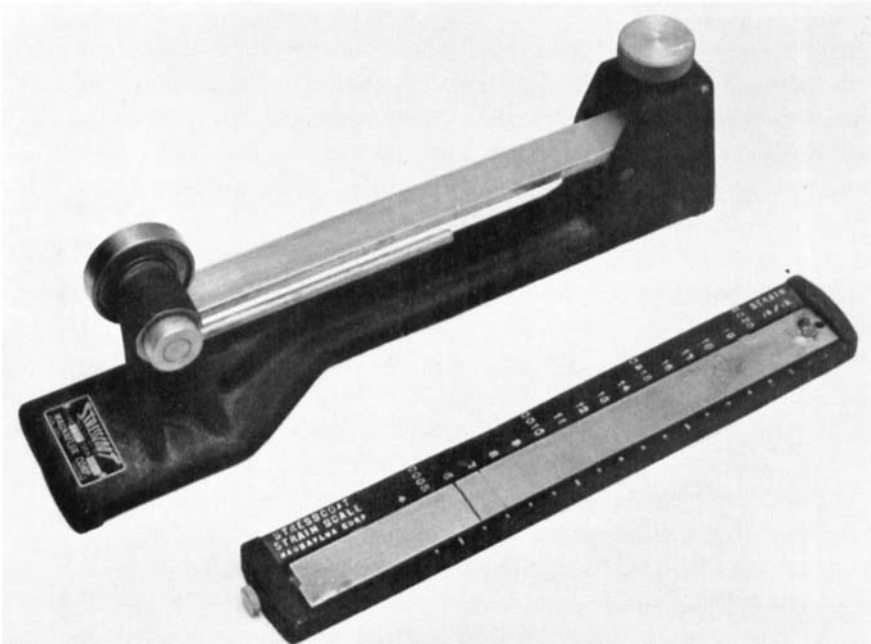


Fig. 1.

Calibration rod mounted in the testing device which produces a constant stress on the rod. The higher the lacquer sensitivity, the further the cracks extend down the surface of the rod. Next to it a calibration rod in the measuring-stick, which shows a specific strain of 0006 in/inch, representing the actual sensitivity of the lacquer.

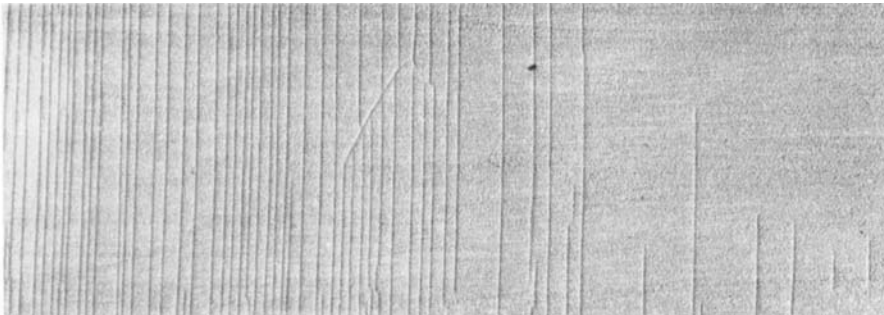


Fig. 2.

Calibration rod with cracks visualized under obliquely directed light.

In order to emphasize them, a special red dye is available which is brushed over the tested surface, where it penetrates into the cracks. A disadvantage of this dye treatment is that the lacquer loses its strain sensitive properties, which makes it impossible to increase the load and record the resulting new cracks. Another method to make the cracks more visible is provided by using an electrostatic powder, "Statiflux", which collects along the cracks. With this method the sensitivity of the lacquer remains intact. A third, and extremely simple method, is to mark the cracks, as they appear, with a fine paintbrush dipped in india ink.

If the specific strain under which the lacquer cracks is known, the method may also be used for qualitative measurements. It is more complicated to use, however, and less reliable than the strain gauge method, but as a qualitative complement to the latter it is extremely useful.

In studies of bone by these methods, the bone is regarded as a hollow structure and the distribution of the strains is measured at the surface. The actual stresses acting in the trabecular system inside the bone cannot be measured directly, but as they will be projected onto the surface at the sites of attachment of the trabeculae to the wall of the structure, one may also, indirectly, record the changes in the strain pattern inside the bone.

In static loading, in which the femur was oriented vertically and the femoral head placed in line with the center of the supporting surface, with the load applied to the head in the same line, the first cracks appeared on the superior aspect of the neck, slightly lateral to the center. (Fig. 3). This concentration of cracks indicated the site of highest tensile strain. With increasing load, further cracks appeared on the lateral aspect of the shaft. The highest compressive strain was found on the inferior cortex of the neck. Additional cracks arose on the superior medial aspect of the femoral shaft when the load was further increased. On the aspect of the bone subjected to compressive strain, the load required to produce cracks was higher than in the area of tensile strain. The cracks were oriented perpendicular to the long axis of the loaded area. These results confirmed Evan's concept of the femur behaving like an eccentrically loaded column subjected to a bending action. Tensile strain was produced on the convex aspect of the bone, compressive strain on the concave aspect. (Fig. 4).

In another series of tests, static loads were applied to the head, with the long axis of the neck kept in horizontal position and the supporting

Fig. 3.

Proximal end of the femur mounted vertically and loaded in an Amsler compression machine. The highest strain appears on the superior lateral aspect of the shaft and on the superior aspect of the neck.



surface at the distal end of the neck. (Fig. 5). The loads were applied in five different positions, A-E (Fig. 6), achieved by rotation around the long axis of the neck. In position A the inferior cortex of the neck was directed upwards and was the site of highest tensile strain, in B it was the anterior cortex, in C the anterior-superior cortex, in D the posterior-superior cortex, and in E the posterior cortex. The area subjected to the most extensive tensile strain was in each instance treated with Stresscoat. In all tests, lacquer with a sensitivity of 0.0009 inches/inch was used. The tests invariably showed that the minimum load necessary to create a tensile strain in the loaded surface sufficient to produce cracks, was highest in position, A. (Fig. 7).

The main direction of the cracks was always perpendicular to the long axis. The first cracks appeared on the distal half of the neck, that is, at the site of highest strain. The dimensions of the neck, with a smaller diameter in the sagittal plane as compared to the frontal plane and consequently a higher degree of rigidity in the latter, as well as the larger dimensions of the inferior cortex explain the higher loading

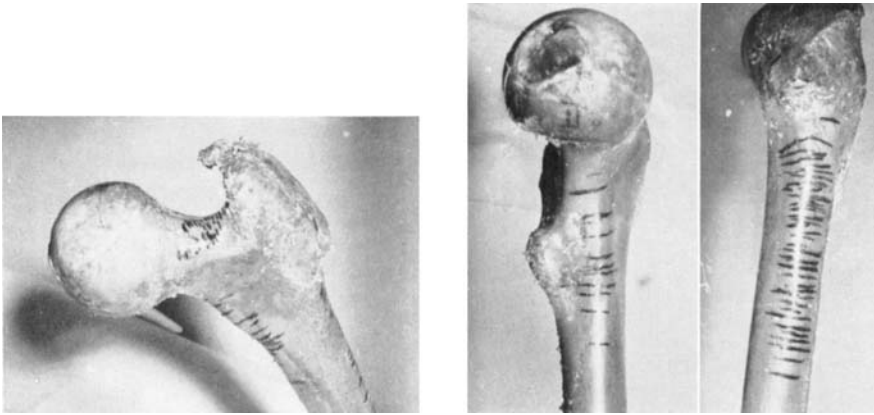


Fig. 4.

Proximal end of the femur under vertical loading. Tensile strain is produced on the superior cortex of the neck and the superior lateral aspect of the shaft. Compressive strain appears laterally on the inferior cortex of the neck and on the superior medial aspect of the shaft. The cracks on the aspect of the bone under tensile strain extend further down the shaft than in the area of compressive strain.

values obtained in position A. The tests were made on fresh autopsy bone, stored in a deep-freezer.

Position	Average load under which the first cracks appeared
A	62.5 kg
B	34 -
C	35 -
D	46 --
E	29 -

In order to estimate the influence of this method of storage on the results, the same tests were repeated on two femurs stored at room temperature for 6 months. Similar strain patterns were obtained in these tests, but it proved necessary to increase the load required to produce cracks by 30 per cent, on an average, showing that the elasticity of the bone had decreased.

SUMMARY

The Stresscoat technique may be profitably employed in studies of bone. The method is elaborate and required training. For quantitative determinations, the method is not as reliable as the strain gauge

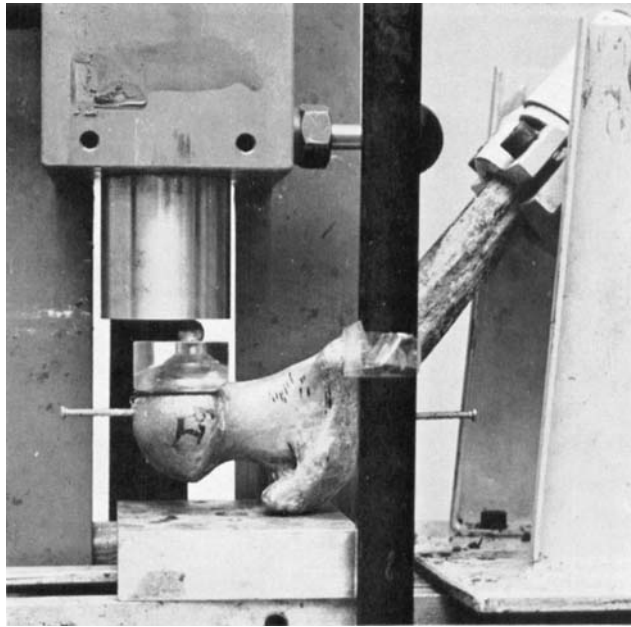


Fig. 5.

Proximal end of the femur with the load applied to the inferior cortex of the head and with the neck in a horizontal position.

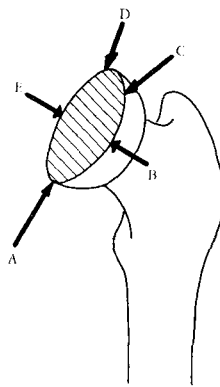
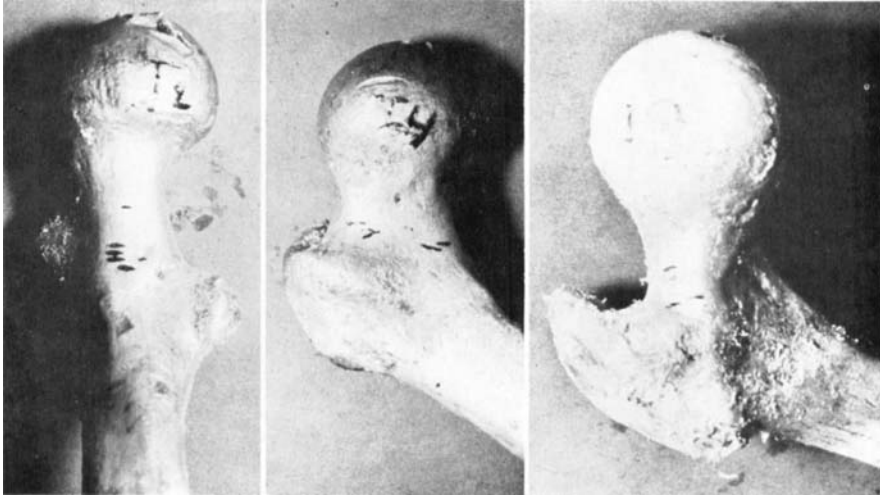


Fig. 6.

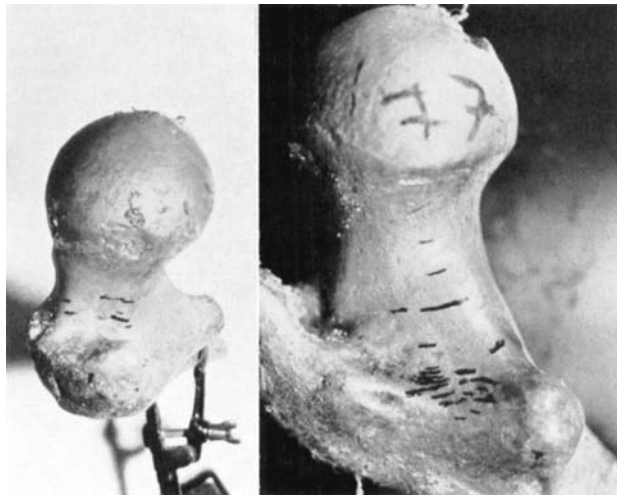
Diagram of the load directions used in the test described in the text, in which the head was loaded with the long axis of the neck oriented horizontally.



A

B

C



D

E

Fig. 7.

The pictures show the patterns of strain produced by loading the femur in positions A-E, as described in the text. Note that the first cracks appear on the lateral aspect of the neck, at right angles to the long axis of the neck.

technique. In stress and strain analysis of a structure as complex as bone, it is, on the other hand, a necessary complement to the strain gauge technique, as it indicates the direction of the stresses on the surface of the bone and the site of maximum strain.

Preliminary studies were made on the femur. Forces from different directions were applied to the femoral head and the distribution of the stress in the femoral neck was recorded. The concentration of the cracks in the lacquer indicated the site of greatest strain. The number of cracks increased with increasing force. The cracks were orientated largely perpendicular to the longitudinal axis of the femoral neck. The site and number of cracks varied with the magnitude and direction of the force. The smallest force necessary to produce cracks was largest when the greater trochanter was supported in external rotation while the inferior part of the head was loaded.

RESUME

La technique de la couverture de tension peut être profitablement utilisée pour l'étude des os. La méthode doit être appliquée avec soin et demande de l'entraînement. Pour les déterminations quantitatives, cette méthode n'est pas aussi sûre que la technique de la jauge de l'effort. Dans l'analyse de la tension et de l'effort d'une structure aussi complexe que celle de l'os, il faut d'un autre côté un complément à la technique de la jauge de l'effort indiquant la direction des tensions sur la surface de l'os et le siège de l'effort maximum.

Des études préliminaires ont été faites sur le fémur. Des forces venant de directions différentes ont été appliquées à la tête fémorale et la distribution de la tension sur le col fémoral a été enregistrée. La concentration des craquements de la laque indique le siège du plus grand effort. Le nombre des craquements augmente avec l'accroissement de la force. Les craquements ont été orientés d'une manière largement perpendiculaire à l'axe longitudinal du col fémoral. Le siège et le nombre des craquements varient avec l'importance et la direction de la force. La plus petite force nécessaire pour produire un craquement a été observée lorsque le grand trochanter était supporté en rotation externe, alors que la partie inférieure de la tête était en charge.

ZUSAMMENFASSUNG

Die "Stresscoat" Technik kann mit Vorteil zur Untersuchung von Knochen angewendet werden. Die Methode ist kompliziert und erfordert

Übung. Für quantitative Bestimmungen ist die Methode nicht so verlässlich wie die "Straingauge" Technik. In der Analyse von Belastung und Spannung einer so zusammengesetzten Struktur wie der des Knochens ist sie andererseits eine notwendige Ergänzung der "Strain-gauge" Technik, da sie die Richtung der Beanspruchung an der Oberfläche des Knochens und den Sitz der grössten Belastung anzeigt.

Vorhandsuntersuchungen wurden am Femur vorgenommen. Kräfte wurden in verschiedenen Richtungen am Schenkelkopf angesetzt und die Verteilung der Beanspruchung auf den Schenkelhals wurde verzeichnet. Die Konzentration der Sprünge im Lack zeigte den Sitz der grössten Beanspruchung an. Die Zahl der Sprünge nahm mit der Vergrösserung der Kraft zu. Die Sprünge waren grösstenteils senkrecht zur Längsachse des Schenkelhalses gerichtet. Der Sitz und die Zahl der Sprünge wechselte mit der Grösse und der Richtung der Kraft. Die kleinste Kraft, die notwendig war um Sprünge hervorzurufen, war am grössten (am wirksamsten?) wenn der grosse Trochanter in Aussenrotation unterstützt wurde während der untere Teil des Kopfes belastet wurde.

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