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STRESS TRAJECTORIES IN THE PATELLA

Study by the Photoelastic Method

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During the flexion-extension movements of the knee joint, the patella sweeps freely up and down in a range of 5–7 cms (Fick 1911). On the final forceful extension it is subjected to a force of tension generated by the contraction of the quadriceps muscle that tightens its tendinous insertions and pulls the patella upward. In full flexion the patella is also subjected to a force of tension that pulls it downward. Both forces press he patella against the underlying bone so that it cannot move.

Analysis of magnitude and direction of these forces are not well established, and it is difficult to understand them from a mechanical point of view. However, stresses and strains in the patella can be quantitatively analysed as has been done with other bones (Kummer 1966, Milch 1940) by means of the photoelastic method, studying models made of transparent material that becomes doubly refractive when stressed. In this method, the refractive axis coincides with the principal stress axis, and the difference in velocity change of light transmission through these two axes is proportional to the difference in magnitude of the principal stress; thus the lines of constant difference between stresses can be made visible.

In order to establish the stress trajectories in the patella a 83 × 63 mm Epoxy resin model of the patella was made and subjected to a 75 kp force for experimental stress analysis in the polariscope.

The following assumptions were made:

(1) The patella has a uniform thickness: 13.5 mm.
(2) The force in the muscle is evenly distributed along the superior and inferior borders.

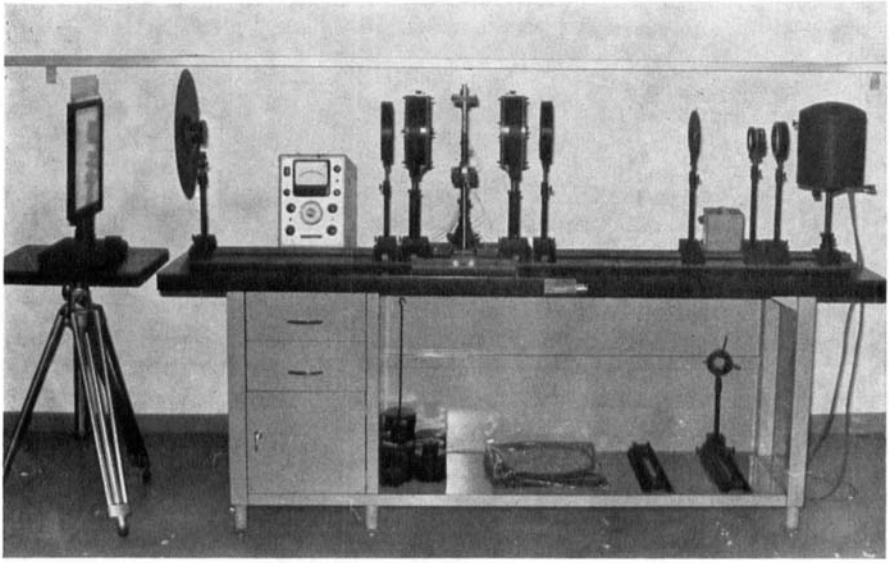

Figure 1. Polariscope.

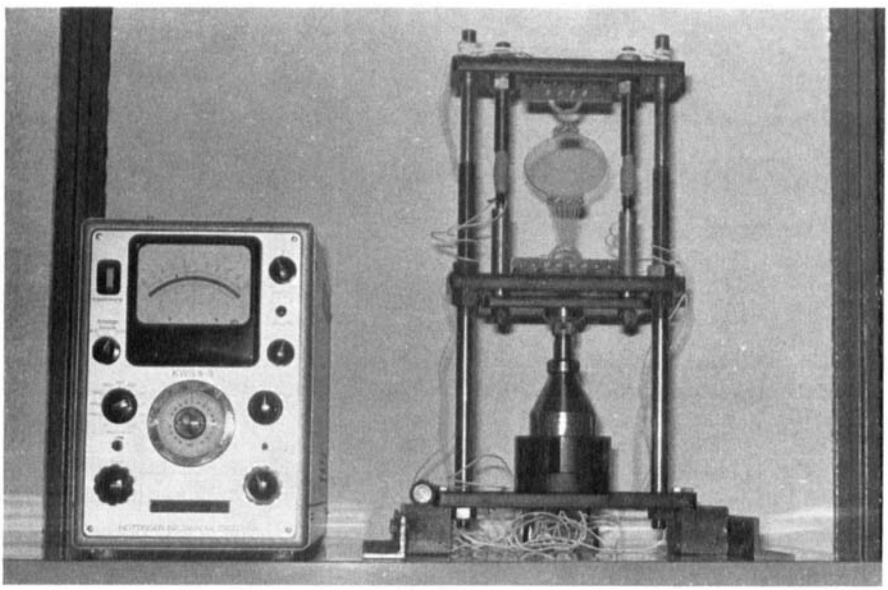

Figure 2. Model suspension in tensometer.

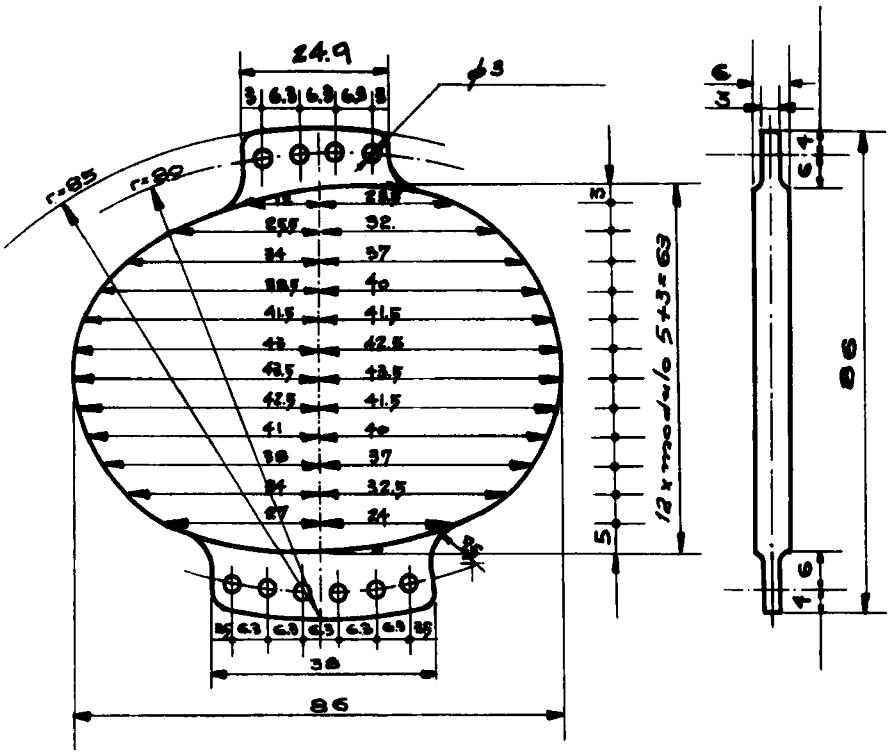

Figure 3. Model dimensions in mm.

(3) The suspension shown in Figure 2 approximately resembles the actual suspension of the patella in the musele.
(4) The load is such that the single tensile force acts on the patella without any friction or perpendicular forces to the patella.

METHOD

In order to find the stress distribution, a lens-type polariscope Riken Keiki type PHS-150 was used (Figure 1). The dimension of the polarizer was 150 mm. The light source was an incandescent filament lamp of 300 W. To provide monochromatic light, a filter transmitting green light at 5461 Angström was used. The model was made of Epoxy resin with material fringe value f $\sim$ 1 mm/kg. The thickness of the model material plate was 6 mm. The model dimensions are given in Figure 3.

To measure the force, a specially made tensometer utilizing a strain guage technique was applied (Figure 2). The usual parameters of isoclinics were obtained using white light and plane polariscope arrangement. Isochromatics were found by circular polariscope arrangement (with quarter wave plates) and with monochromatic

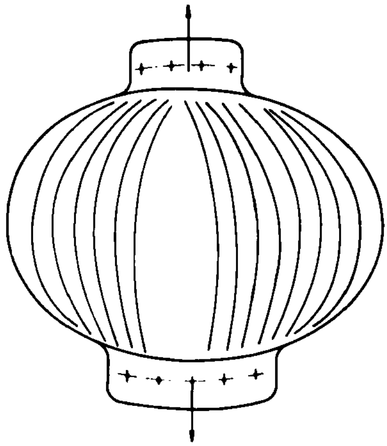

Figure 4. Isostatic lines.

light. Both dark-field and light-field arrangements were used. For some patterns the tracing technique, using a screen together with a special converging lens was employed. Some of the patterns were obtained using a Canon camera.

Isostatic lines were established by the isoclinic pattern shown in Figure 4. The principal stresses were found by the shear difference method which implies the determination of the isostatic and the isochromatic distribution in the model.

To verify the experimentally found details, theoretical principal stresses were calculated for a number of points in the model. It was assumed that the stresses in the horizontal and vertical direction in the model consisted of two Boussinesq stresses and a hydrostatic compression equal to $\frac{2P}{d\pi t}$ (a solution similar to that developed by Michell in 1900 for a cylinder (6). The following equations were used in the calculations (Timoshento & Goldier 1951)).

$$Zx = \frac{p}{2\pi}\left[2\theta + 2 \sin \theta\right]_{\theta_1}^{\theta_2} \qquad (1)$$

$$Zy = \frac{p}{2\pi}\left[2\theta - 2 \sin \theta\right]_{\theta_1}^{\theta_2} \qquad (2)$$

$$Zxy = \frac{p}{2\pi}\left[\cos 2\theta\right]_{\theta_1}^{\theta_2} \qquad (3)$$

where p is the stress in kp/cm^2 along the line of application of the total load which amounted to 75 kp. The angles Θ_1, Θ_2 were measured between the vertical and horizontal orientations to the point in question (Figure 5). The contribution of the load on one side was added to the contribution of the load on the opposite side. To make the load equal to O at the boundaries of the model, it was assumed that a compressive force of 12.7 kp/cm² was applied to the model. The total stress in horizontal direction was:

$$Zx = \frac{p_1}{2\pi}\,[2\theta + \sin 2\theta]\,_{\theta_1}^{\theta_2} + \frac{p_2}{2\pi}\,[2\theta + \sin 2\theta]\,_{\theta_4}^{\theta_3} - 12.7 \tag{4}$$

Similarly, in the vertical direction

$$Zy = \frac{p_1}{2\pi}\,[2\theta - \sin 2\theta]\,_{\theta_1}^{\theta_2} + \frac{p_2}{2\pi}\,[2\theta + \sin 2\theta]\,_{\theta_3}^{\theta_4} - 12.7 \tag{5}$$

where $p_1 = 33.3$ kp/cm² and $p_2 = 50.3$ kp/cm².

For the shearing stress the contributions are unaffected by hydrostatic compression and becomes:

$$\tau = \frac{p_1}{2\pi}\,[\cos 2\theta]\,_{\theta_1}^{\theta_2} - \frac{p_2}{2\pi}\,[\cos 2\theta]\,_{\theta_3}^{\theta_4} \tag{6}$$

The maximum principal stress therefore is given by

$$\tau_1 = \frac{Zx + Zy}{2} + \sqrt{\left(\frac{Zx - Zy}{2}\right)^2 + \tau xy_2} \tag{7}$$

Both the experimental and theoretical stress distribution are shown in Figure 5. The values of the stresses at points along the boundaries indicate that Eqs. (4), (5), and (6) were approximately correct.

Table 1. Experimental principal stresses along lines 3 and 4 in Figure 5

Line 3 (kp/cm²)	Line 4 (kp/cm²)
1.73	1.95
7.39	7.00
13.70	9.97
21.21	22.00
24.85	28.21
29.17	30.83
26.67	25.00
20.40	17.86
10.80	9.12
8.05	4.90
2.20	0

Principal stresses at 20 mm intervals begin at points A and B in Figure 5.

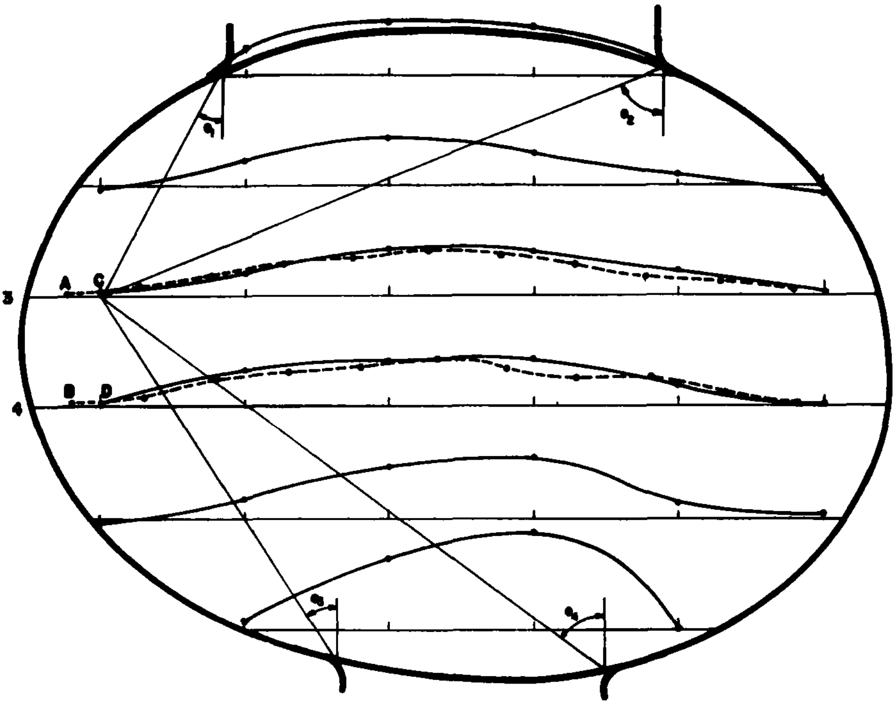

Figure 5. Experimental and theoretical distribution of principal stresses.

——— Theoretical distribution
- - - - - Experimental distribution
4.9 kp/cm² in prototype
10 kp/cm² in model

RESULTS

From the isochromatic and isoclinic fringe patterns the principal stresses were deduced (Dailey & Rilley 1965). An approximate theoretical formula was derived to find the theoretical distribution of the stresses for comparison. As can be seen from Figure 5, which shows the principal stresses, and Tables 1–2, the theoretical and experimental stresses are of the same magnitude. It appears that the lower part of the model is subjected to higher stress than elsewhere. The outer parts, beyond the zero fringe, carry very little load and from a strength point of view could be ignored. However, undoubtedly, these parts serve other purposes such as stability of the element.

The isoclinic pattern obtained (Figure 6) using 10 different angular positions of the polarizer shows a limited region of stresses inclined

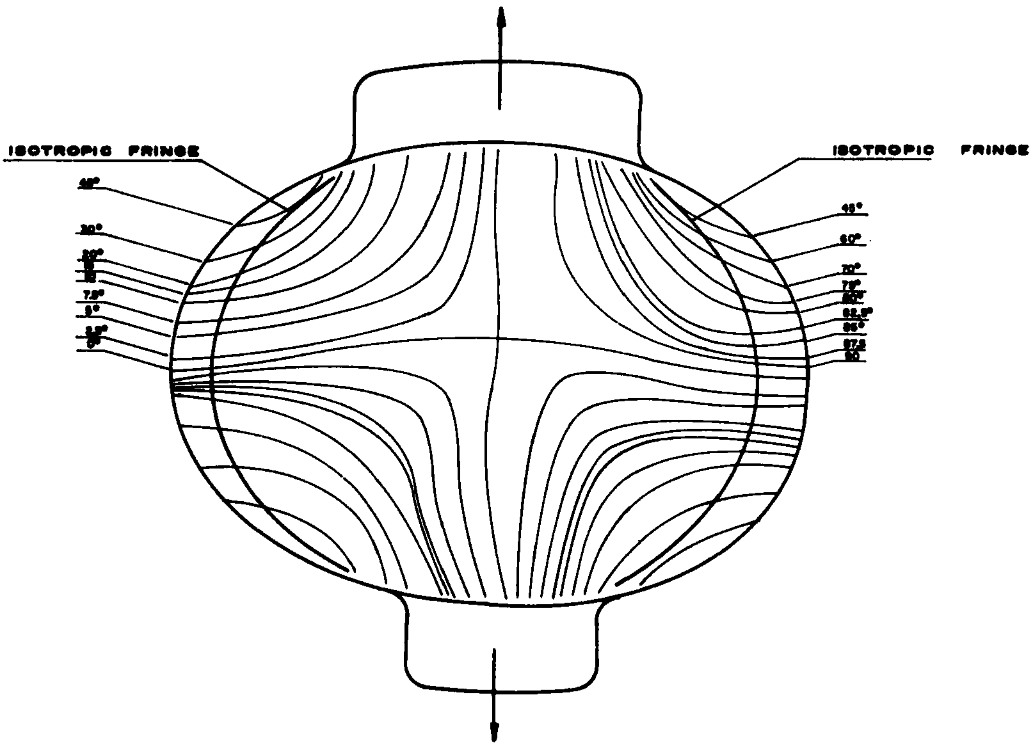

Figure 6. Isoclinics pattern.

Table 2. Theoretical principal stresses along lines 3 and 4 in Figure 5

Line 3 (kp/cm^2)	Line 4 (kp/cm^2)
1.36	1.37
15.33	24.97
31.22	31.23
29.11	32.11
17.43	12.87
0.48	0.64

Principal stresses at 40 mm intervals begin at points C and D in Figure 5.

30° or more (Figures 7 a and 7 b). Most of the force transmitted across the model is due to stresses in the vertical or almost vertical direction. This should be expected owing to the geometrical form of the element and the manner in which the forces are applied.

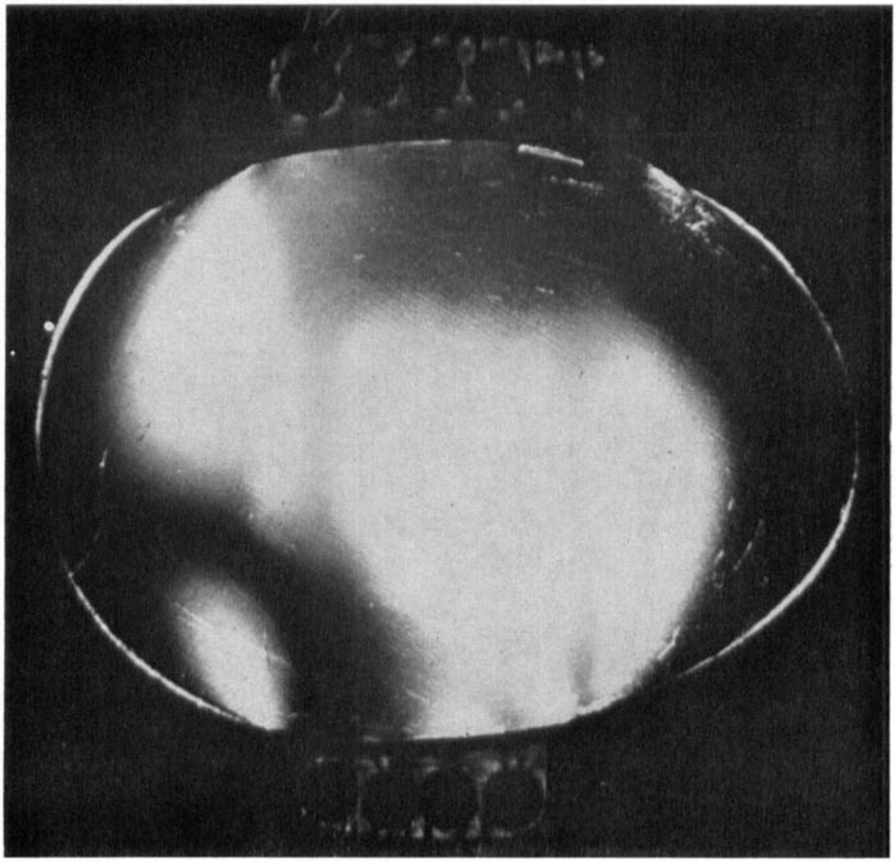

Figure 7a.

Figure 7. Isoclinics patterns a at 30°, b at 90°.

Figure 8 shows the isochromatic pattern, that is, the lines along which the difference between the two principal stresses is constant. A concentration of fringes appears in the vicinity of the inferior border, indicating a higher stress level here. The fringe pattern is irregular due to the lack of symmetry in the configuration and loading.

From the data it is clear that the maximum principal stresses are tensile, whereas the other principal stresses sometimes are compressive particularly in the central part of the element. In other words, the maximum shearing stress is high here.

Figure 5 shows two scales; one for the model and one for the prototype. The latter was obtained using an average thickness of

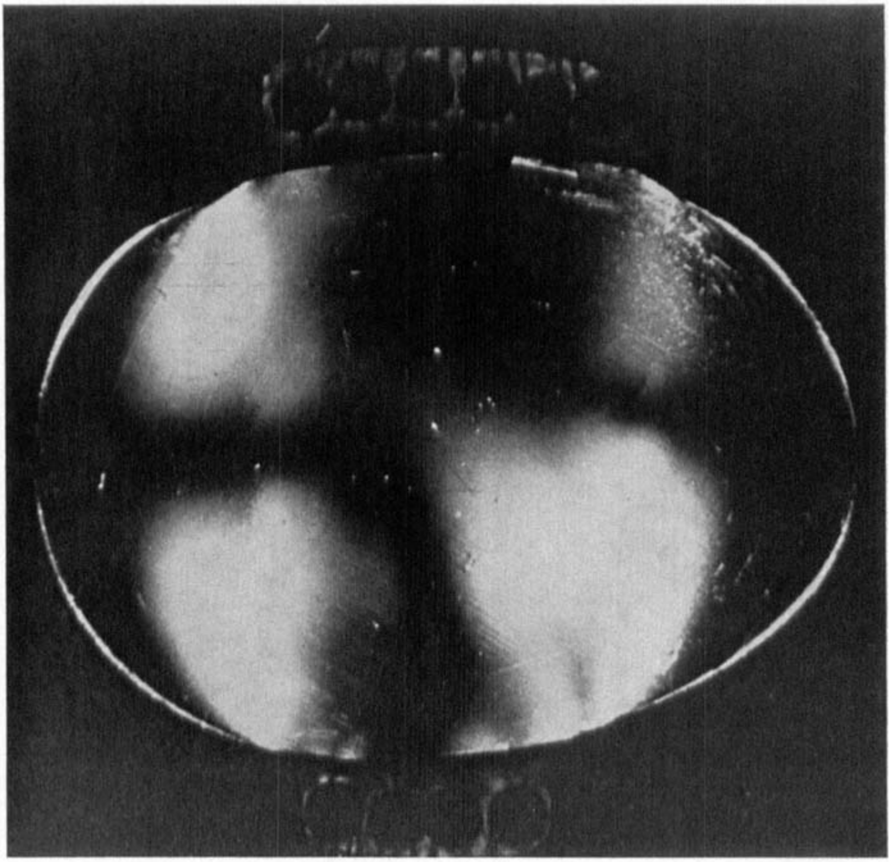

Figure 7b.

13.5 mm of the prototype and a force of 42 kp in the muscle of an average male person (Steindler 1955).

DISCUSSION

During full range of active mobility of the knee joint in flexion-extension, the patella is under the action of two opposite forces applied over a common axis that pull it apart: one is supplied directly by the quadriceps muscle and the other by the hamstring muscles acting via the ligamentum patellae.

The forces exerted by quadriceps acting in the knee joint during active extension have been calculated in different positions, and the maximum moment has been recorded at 105–120° with reduction on

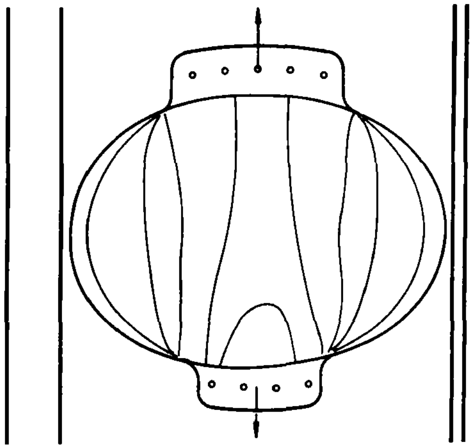

Figure 8. Isochromatic.

further flexion and extension (Lindahl et al. 1969). However, the distribution of these forces on patella is not known. Based on the experimental and theoretical analysis presented, the stress trajectories of the forces applied in the patella seem to conform to the following pattern:

(1) The forces applied in patella are transmitted vertically.
(2) The lower part of the patella is subjected to higher stresses than elsewhere. Transverse fracture caused by violent contraction of the quadriceps while the knee is being forcibly bent by the weight of the body is most commonly situated in the lower half as the triangular shaped patella.
(3) The principal stresses are tensile, but in the central part they are compressive; the maximum shearing stress is higher here. In chondromalacia patellae the degenerative changes in the articular cartilage may thus be the result of a compressive stress.

SUMMARY

Using the photoelastic method, experimental and theoretical stress analyses were calculated in the patella using a model of this bone made of Epoxy resin subjected to a force of 75 kp. Most of the forces applied to the model were transmitted vertically with higher stress level in the inferior border. The principal stresses are tensile, but in the central

part they are compressive. This can explain some details of the transverse fracture of the patella by indirect violences as well as chondromalacia of this bone.

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