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A PHOTOELASTIC STUDY OF A MODEL OF THE PROXIMAL FEMUR

A Biomechanical Study of Unstable Trochanteric Fractures I

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In an attempt to standardize an experimental model for biomechanical studies of unstable trochanteric fractures, acrylic models of the proximal femur were investigated by the photoelastic technique. By matching the stress distribution in the acrylic models to those calculated by Pauwels, it was found that the optimal femoral shaft and resultant hip joint force angles were 5° and 6° to the vertical, respectively. The abductor muscle pull was determined to be 55 per cent of the resultant hip joint force at 15° medial inclination to the vertical.

Key words: biomechanics; femoral neck; joint forces

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Wolff (1870) described the architecture of the trabecular system in the femoral neck as being in accordance with the mathematical stress trajectories. A number of papers concerning the transmission of forces from the hip joint to the femoral shaft have confirmed his theories (Backman 1957, Inman 1947, Koch 1917, Tobin 1955, Williams & Svensson 1971) either through mathematical calculations or in laboratory investigations on cadaveric bone.

Pauwels (1935) introduced a simple mathematical analysis of the force vectors around the hip joint in order to calculate the load on the femoral head. Several more recent papers have discussed the magnitude and direction of the hip joint force and the abductor muscle force as well as the inclination angle of the femoral shaft. Somewhat conflicting results have been stated, however, concerning the relationships between these variables.

The aim of the present studies is to clarify the mechanical behaviour of different hip nail-plates in osteosynthesis of unstable trochanteric fractures. For this purpose, however, a standardized experimental arrangement is needed as regards the inclination angles of the femoral shaft, the hip joint force and the abductor muscle force, as well as the relation between the magnitudes of the two forces. To simplify the static experiments these variables will be considered in the frontal plane only.

The photoelastic technique (Föppl & Mönch 1972) has been widely used by engineers in the analysis of constructions which are difficult to describe in mathematical terms. Brekelmans et al. (1972) mentioned this method as being useful in determining the mechanical behaviour of bone, although the anisotropy of bone was not taken into account. The photoelastic technique has been applied to hip models (Fessler 1957, Milch 1940, Ruszkowski & Muftic 1972) showing stress patterns corresponding with the stress trajectories in the femoral neck (Wolff 1870, Koch 1917, Pauwels 1935, 1973).

The present paper will present the results of the photoelastic technique applied to two-dimensional models of the proximal femur to find a standardized experimental model with reference to the parameters mentioned.

MATERIALS AND METHODS

Photoelasticity (Föppl & Mönch 1972) is based on the fact that some transparent, isotropic solids become bi-refringent under mechanical load. For experimental purposes an exact model of the construction is made from a photoelastic material (e.g. Araldite-B®). The model is loaded and illuminated with polarized light in a polariscope. The difference between the principal stresses at any point in the model is proportional to the relative retardation of the two component rays of polarized light that pass through the point. When the relative retardations are equal to an integral multiple of the wavelengths of the light used, no light is transmitted. In monochromatic polarized light the lines of constant shear stress appear as black bands – the isochromates. In white polarized light the neutral axis, which is stress free, is seen as a dark band, while the isochromates appear in the colours of the spectrum. The isochromates are numbered (i.e. ordered) from the neutral axis which is called the zero-isochromate. The number of isochromates thus increases with increasing mechanical stress.

Based on measurements made on X-rays of normal hip joints from five patients, two-dimensional models of the proximal femur were manufactured in polyester (Araldite-B®). An idealized model with a femoral neck angle of 130° and one of 140° were made.

The model was fastened to a steel socket and placed in the polariscope (Tiedemann A 159, W. Germany). The model was loaded vertically (Figure 1) by a steel bar (weight = 6.8 Newton) supplemented with a load proving ring (Tiedemann H 256 M, W. Germany), weighing 3.2 N, on which a screw press was applied – the total load being

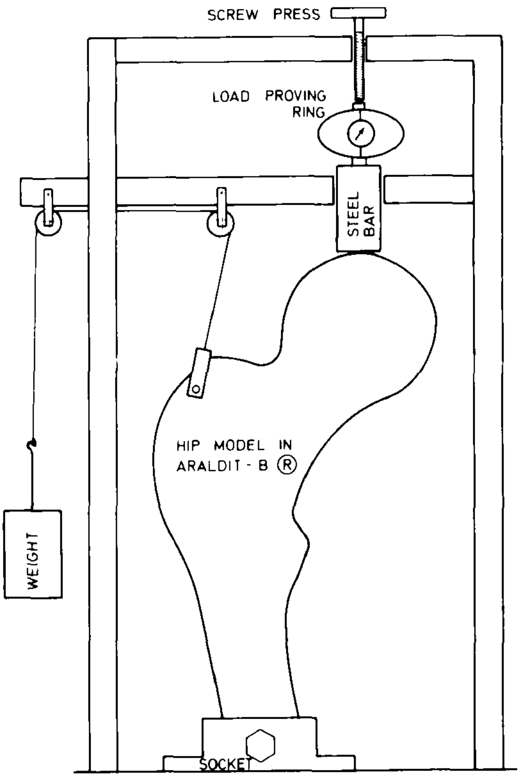

Figure 1. Experimental arrangement.

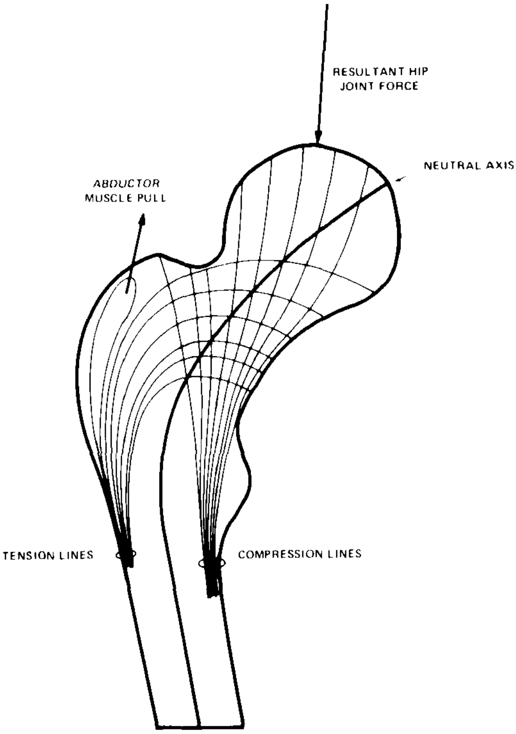

Figure 2. Reconstruction of stress trajectories. (Koch 1917, Pauwels 1973.)

equivalent to the resultant hip joint force (J). The abductor muscle pull was applied by weights (= 70 N) over a system of pulleys to a hole drilled in the greater trochanter of the model. The model was viewed in polarized light and the picture on the analyzer screen was photographed and compared to the stress trajectories (Figure 2) reconstructed from Koch (1917) and Pauwels (1935, 1973).

The force vectors and the inclination angles are shown in Figure 3.

In the experimental series the parameters were varied as follows, although corrections were made according to the vertical loading of the models:

ψ = femoral shaft inclination: 5°, 10°, 15°
φ = hip joint force inclination: 6°, 11°, 16°
Θ = abductor pull direction: 10°, 15°, 20°
$\frac{M}{J} = \frac{\text{abductor muscle force}}{\text{hip joint force}}$: 0.55, 0.60, 0.65

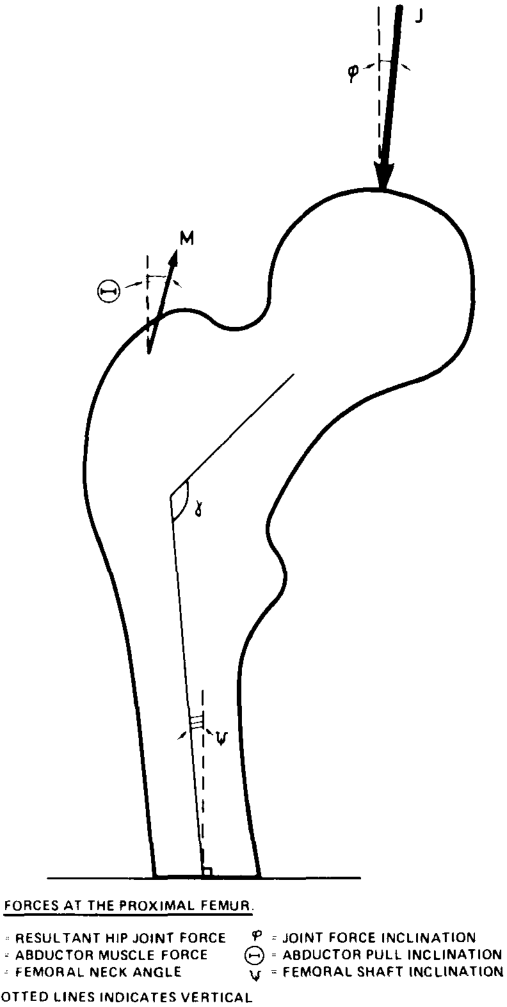

Figure 3. Forces at the proximal femur.

These figures represent average values from the papers referred to in the discussion.

RESULTS

Sixty-five experiments were performed with the 140° femoral neck model and 77 experiments on the model with a 130° femoral neck angle. Examination of the photographs from the experiments on both models showed that the optimal arrangement with reference to the parameters mentioned consisted of a femoral shaft inclination (ψ) of 5° in combination with a joint force inclination (φ) of 6° and an abductor pull inclination (Θ) of 15°. The magnitude of the abductor muscle force (M) was determined to be 55 per cent of the resultant hip joint force (J). These values were chosen as the stress patterns in the model (Figure 4 and Figure 5) corresponded best with the stress trajectories shown in Figure 2. Stress patterns not corresponding to these trajectories were rejected, as demonstrated in Figure 6 ($\psi = 15°$, $\varphi = 11°$, $\Theta = 20°$, $M/J = 0.55$).

In this series of experiments the influences of an increased femoral shaft inclination (ψ) and an increased joint force inclination (φ) were similar. Both displaced the neutral axis laterally (Figure 6) and with increased inclination of the model, the stress patterns in the medial part of the neck and shaft were changed from compression to tension (Figure 7).

The direction (Θ) and magnitude of the abductor muscle pull in relation to the joint force (M/J) did not show any great effect on the stress patterns in the model. In this series Θ was determined as 15° and M/J as 0.55. Altering the abductor pull direction to $\Theta = 10°$ displaced the neutral axis slightly laterally and $\Theta = 20°$ involved a slight increase of the number of isochromates in the medial part of the shaft. Increasing the abductor muscle force in relation the resultant hip joint force increased the bending moment and displaced the neutral axis slightly in the lateral direction.

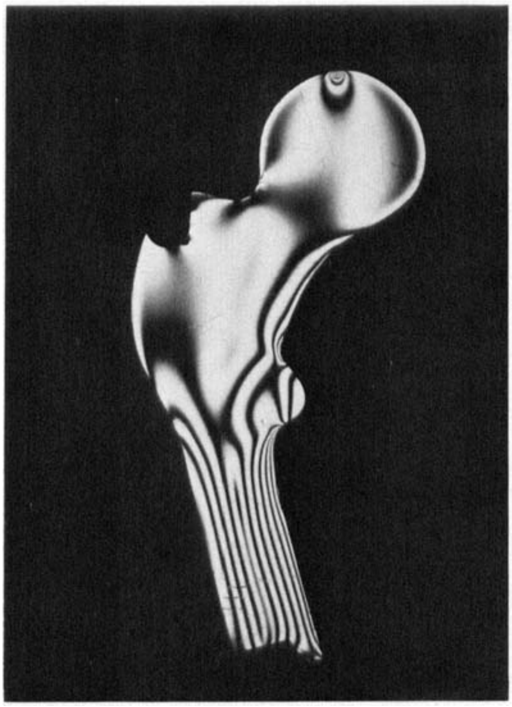

Figure 4. Normal hip model. 130° femoral neck angle.

$\psi = 5°$, $\varphi = 6°$, $\Theta = 15°$, M/J = 0.55

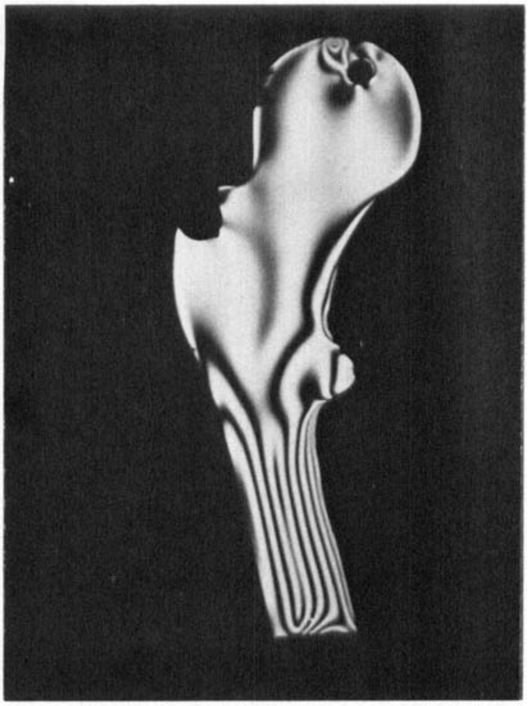

Figure 5. Normal hip model. 140° femoral neck angle.

$\psi = 5°$, $\varphi = 6°$, $\Theta = 15°$, M/J = 0.55.

DISCUSSION

Two-dimensional studies of hip models have been carried out using the photoelastic technique (Haboush 1952, Milch 1940, Pauwels 1951, Ruszkowski & Muftic 1972) and the method has been considered useful in experimental research by Brekelmans et al. (1972). A three-dimensional photoelastic technique was introduced by Hetenyi (1939) and has also been applied to hip models (Fessler 1957, Williams & Svensson 1971). This technique is however much more complex and has not contributed an increase in information (corresponding with the complexity) as compared with the rather simple two-dimensional technique; both methods revealed stress patterns corresponding to Wolff's trajectories (Fessler 1957, Milch 1940, Ruszkowski & Muftic 1972).

In the present study it has been the author's aim to consider the force vectors and the femoral shaft inclination in a two-dimensional static study in the frontal plane, as this is the most practical arrangement for further laboratory investigations. It is obvious that the results obtained can not directly be used clinically as the eccentric position of the centre of gravity, the muscle pull from the thigh muscles, the forces of the ligaments and the anteversion of the femoral neck were not considered. The shear stresses are higher in the central plane in the model than average because of the isotropy of the model material. In the experiments the influences of deformations of the model and probable shear forces from torque were not taken into account, but were assumed not to alter the stress patterns.

Accepting the obvious limitations of the technique and the experimental arrangement, the author has found it worthwhile to determine an optimal model with reference to

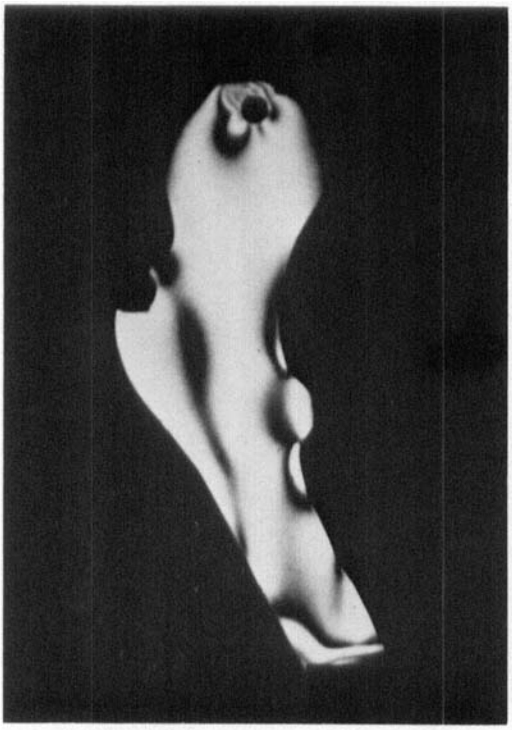

Figure 6. Rejected stress patterns.

$\psi = 15°$, $\varphi = 11°$, $\Theta = 20°$, $M/J = 0.55$

Stress patterns not in accordance with Wolff's trajectories. Neutral axis displaced laterally. The isochromates are tension lines in the medial part of the shaft. There is practically no bending in the neck.

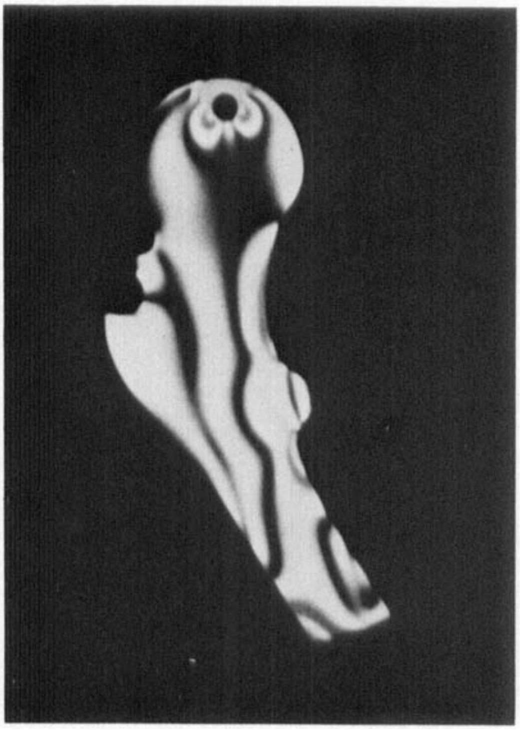

Figure 7. Rejected stress patterns.

$\psi = 15°$, $\varphi = 16°$, $\Theta = 15°$, $M/J = 0.65$.

Neutral axis is the most laterally situated line. The isochromates in the medial part of the neck and shaft are all tension lines demonstrating lateral bending moment.

the aforementioned parameters, as variations of these showed considerable changes in the stress trajectories (Koch 1917, Pauwels 1935, 1973, Wolff 1870). During the past 40 years many attempts have been made to determine the force vectors around the hip joint and somewhat conflicting values have been reported for the femoral shaft inclination (ψ), the resultant hip joint force (J) and its inclination (φ) and the abductor muscle pull (M) and its acting direction (Θ), as well as the relations between the magnitudes of the two forces.

Prior to the present study, calculations were made from values stated in previous papers considering all these variables in studies of the static one-legged stance. Calculated values of M/J varied from 0.40–0.60 (McLeish & Charnley 1970, Pauwels 1935, Rydell 1966, Williams & Svensson 1968) to 0.65–0.75 (Amtmann & Kummer 1968, Denham 1959, Hamacher & Roesler 1972, Inman 1947). In the same studies the joint force inclination (φ) has been reported as being between 6° and 17° and the abductor pull direction (Θ) between 10° and 21°, while the femoral shaft inclination (ψ) has been stated as being between 5° and 15°.

In this series the femoral shaft inclination was determined to be 5° in accordance with Pauwels (1935). The joint force inclination was found to be 6° and the direction of the abductor muscle pull to be 15°, which agrees well with McLeish & Charnley (1970). The magnitude of the abductor muscle pull was determined to be 55 per cent of the resultant hip joint force in accordance with the results of other studies (McLeish & Charnley 1970, Pauwels 1935, Rydell 1966, Williams & Svensson 1968). In conclusion, the author considers the standard experimental arrangement described, as found through photoelastic studies, to be acceptable and very useful for further laboratory investigations of the unstable trochanteric fracture.

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