

Biomechanical changes of hip joint following different types of corrective osteotomy – photoelastic studies

NICOLAE ILIESCU^{1,*}, STEFAN DAN PASTRAMA¹, LUCIAN GH. GRUIONU², GABRIEL JIGA¹

¹ “Politehnica” University of Bucharest, Romania.

² University of Craiova, Romania.

The paper presents the results of some comparative experimental studies that show the biomechanical changes which appear following different types of corrective osteotomy. The photoelastic technique was applied to plane models. The modifications in the stress distribution on the contour after the osteotomy in comparison with the situation before surgery were studied. Three types of osteotomy are considered: valgus osteotomy, varus osteotomy and Chiari pelvis osteotomy. Using the same experimental technique, the distribution of the contact pressure at the interface between the polyethylene cup and the femoral head is investigated, for a total hip prosthesis, as the extreme solution in the case of advanced hip arthroses. Both a normal situation and the malposition of prosthetic components were analyzed.

Key words: corrective osteotomy, hip prosthesis, hip arthroses

1. Introduction

The hip joint, which is the most important joint of the human osteoarticular system, is a ball-and-socket joint having three degrees of freedom. Due to its complex biomechanical functions, it plays an important role in the locomotion process, both for statics and dynamics of the torso. Having a specific architectonic configuration, the femoral joint provides maximum stability by transmitting the weight of the torso to pelvic members. At the same time, it represents the center around which the pelvis modifies its position during walking.

Important modifications in the biomechanics of the normal hip, with arthritic degeneration which evolves quite rapidly over time, appear due to different diseases of this joint. In order to diminish these modifications, surgery is performed, preferably in an early stage, which allows us to avoid limited late solutions.

Some of the most frequent disorders of the hip, possibly leading to hip arthroplasty as the last treat-

ment solution, are the coxarthrosis and the hip dysplasia.

In this paper, some results of comparative experimental research using the photoelastic technique are presented. Different models were used in order to identify the biomechanical changes of the stress state in the case of hip diseases or architectonic defects, in comparison with the normal anatomic situations. Some corrective and repair osteotomies applied in the surgery practice to treat hip joint diseases or anomalies are studied using the same technique. Finally, the biomechanical behaviour of some hip prostheses, both for normal situations and malposition, is studied.

2. Physiopathology of hip joint

Congenital luxation of the hip can be defined as a complete loss of the normal links between the femoral head and the cotyle. This illness can appear at birth

* Corresponding author: “Politehnica” University of Bucharest, Bucharest, Romania, e-mail: nviliescu@yahoo.com

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or later, progressively, as an increase of the femoral head in abnormal position. There are three stages of the hip luxation: i) simple dysplasia of the cotyle with the femoral head, ii) sub-luxation, where the femoral head is in abnormal position, and iii) high luxation, where femoral head has a contact with cotyle on a very small surface [1].

If the orientation defects of the head and cotyle following this illness are discovered at an advanced stage, inter-trochanterian corrective osteotomies for derotation, varus or varus-derotation should be performed. Surgical corrections of the defects of the cotyle are made either to reorient the whole cavity for a better coverage of the head (Salter pelvis osteotomy) or to increase the covering surface (Chiari pelvis osteotomy). For hip dysplasia or luxation with important arthritic modifications, the arthroplasty with total hip prosthesis is performed.

The arthrosis of hip joint is characterized by a flattening of the anteroexternal femoral head and the acetabular support surface that moves to the antero-upper side. These shape changes are responsible for new biomechanical conditions in the hip joint. The spherical head, that had one rotation center in an undeformed state, has more centers after the deformation. The contact surface between the femoral head and acetabulum decreases due to the deformation, thus leading to an important increase of the pressure on the joint surface. The pressure peak, which develops on the reduced contact surface, with time leads to a local destruction of the cartilaginous tissue and appearance of pains [2].

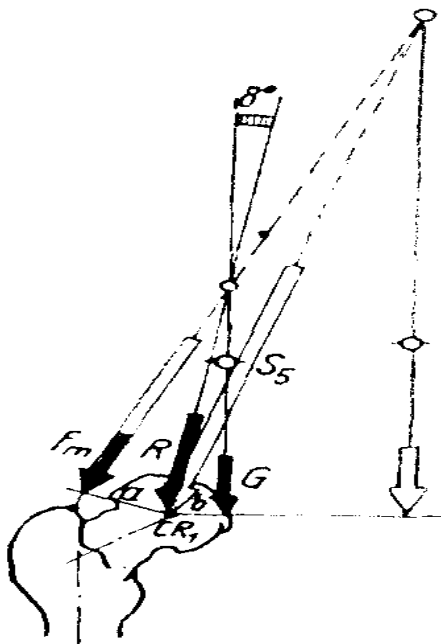


Fig. 1. Deformed femoral head

Unlike a normal hip, where the resultant R of the forces G (weight of the torso) and F_m (force developed by the abductor muscles) is oriented at 16° with respect to the vertical direction, in this case the resultant force decreases and modifies its position: it is oriented slantwise downwards as well, but at an angle of 8° with respect to the vertical position (figure 1). The resultant tends to the vertical position in proportion with the inclination of acetabular surface; consequently, the contact between the femoral head and the acetabulum moves. The reaction force $R_1 = R$ that appears in the contact point is eccentric with respect to R [2], giving rise to a couple that rotates the femoral head (figure 2).

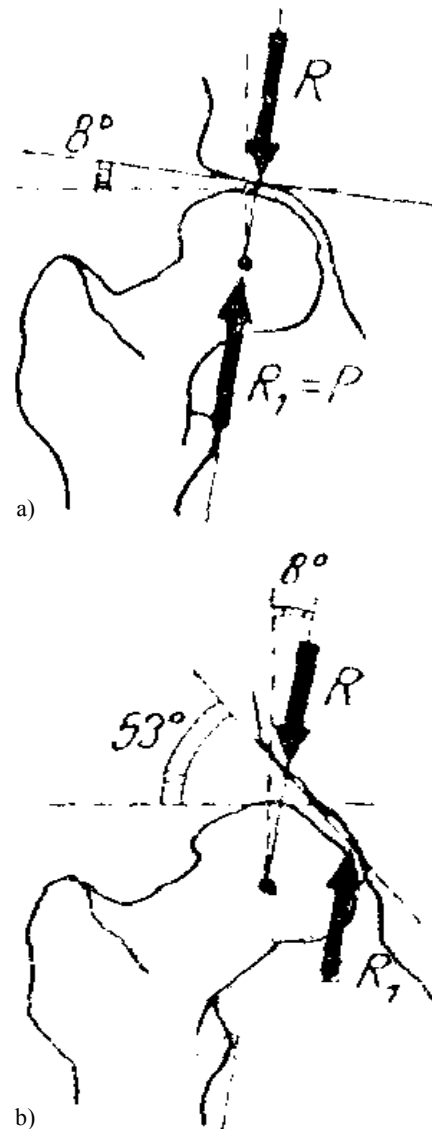


Fig. 2. Normal hip (a), abnormal hip with an inclined acetabulum surface (b)

The cup, the synovial membrane and the round ligament are stressed by this couple, thus favouring the formation of the osteophytes, a characteristic feature

of the hip arthrosis. At the same time, the sliding of the femoral head outwards leads to a plastic deformation of the acetabular surface.

PAUWELS [3] presents some types of osteotomy for surgical treatment of the hip arthrosis. The main goal of such a treatment is to reduce the value of the maximum pressure on the joint surface, both by a decrease of the resultant force R and by an increase of the bearing area on which the force is distributed. When the contact surfaces are reduced, they may be increased by a proper rotation of the femoral head into the cotyle, either inwards or outwards, depending on the joint configuration. In incipient hip arthroses, a varus osteotomy is performed when an inward rotation is necessary for the reconstruction of the joint congruence (figure 3). Thus, the bearing surface is increased, the contact pressure is diminished and the lever arm of F_m is also increased [4].

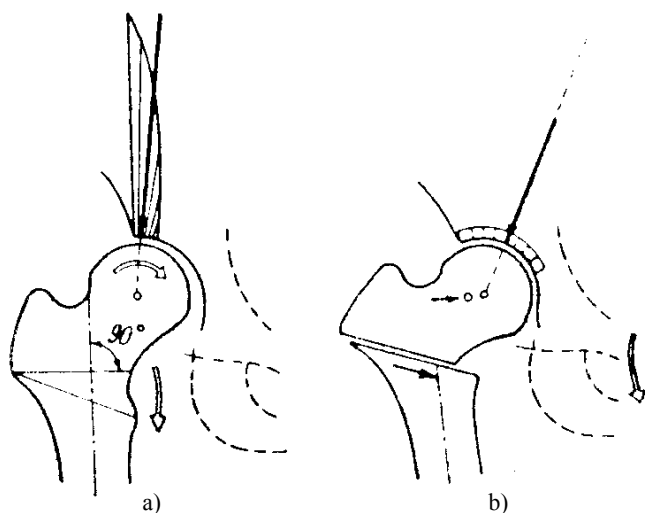


Fig. 3. Incipient hip arthrosis (a), varus osteotomy (b)

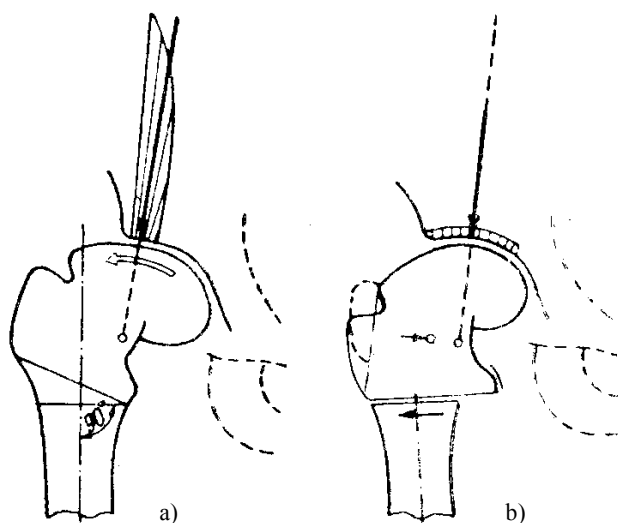


Fig. 4. Advanced hip arthrosis (a), valgus osteotomy (b)

In advanced hip arthrosis, when the rotation is made outwards (figure 4a), the valgus osteotomy (figure 4b) is indicated for the reconstruction of the joint congruence. The bearing is increased in this case while the contact pressure decreases and the resultant force R becomes vertical. The lever arm of the muscular force F_m decreases; in order to keep its couple constant, the value of F_m increases. As a result, a small increase of the resultant force R can be noticed. Since the bearing surface becomes bigger after the osteotomy, the contact pressure remains almost constant.

Another method for enlarging the bearing surface of the hip and thus to diminish the contact pressure is the Chiari hip osteotomy (figure 5). An internal displacement of the whole joint is obtained due to osteotomy of this type, which leads to a reduction of the lever arm of the weight G and to a change of the direction of the force F_m developed by the abductor muscles; this force becomes vertical. These modifications determine a diminution of the resultant R and an increase of the bearing surface of the joint; thus the contact pressure is substantially decreased [5], [6].

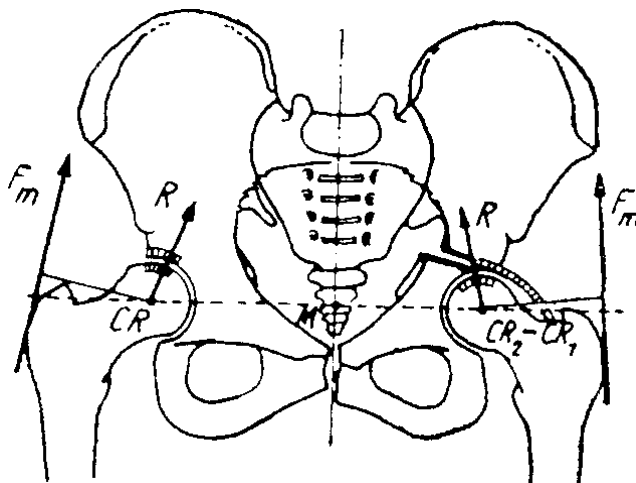


Fig. 5. Chiari osteotomy

3. Experimental research: description and results

The experimental investigations were undertaken on plane photoelastic models of the bone structures examined. The models were machined from an epoxy resin, according to X-ray pictures. In order to better model the real structures, the cartilaginous tissues were made from a thin soft rubber layer. The elastic constants of the materials used in this experiment are given in the table. Special loading devices with cali-

brated weights were used in order to apply the load considered, scaled down to the proper values. All the models were analyzed in a polariscope with white or monochromatic light, whose polarization was either plane or circular. Photographs of the isochromatic fringes were taken for further determination of the principal stress fields on the contours of the models. Before the experimental investigation of the models considered, a calibration of the photoelastic material was made, yielding a value of the photoelastic constant of the material $f_\sigma = 1.85 \text{ MPa/fringe}$.

Elastic constants of the materials used in the photoelastic analysis

Material	Young's modulus [MPa]	Poisson's ratio
Photoelastic epoxy resin	3,200	0.38
Soft rubber	12	0.49

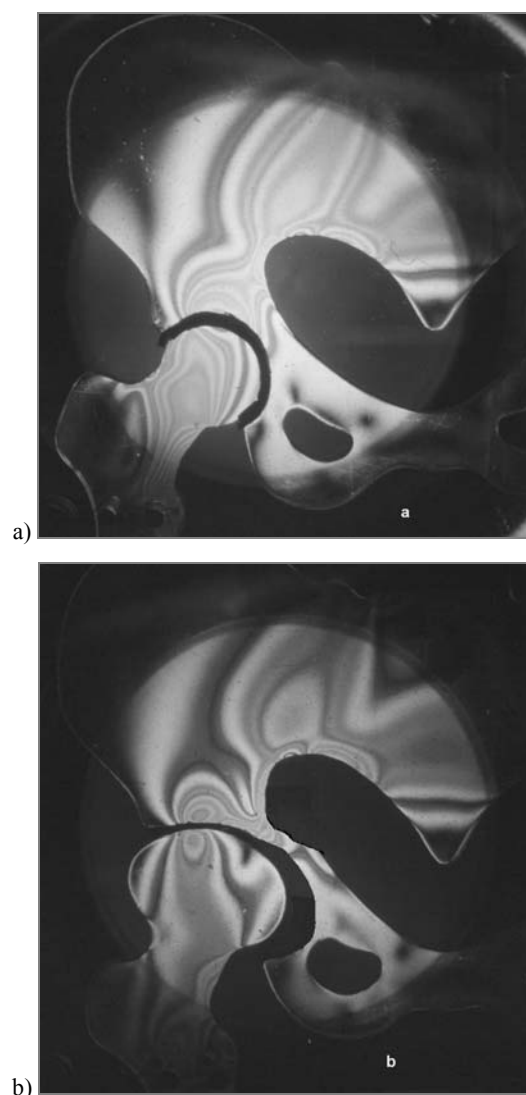


Fig. 6. Isochromatic fringes for normal hip (a), isochromatic fringes for hip with dysplasia (b)

The first study was undertaken in order to show the biomechanical changes that appear in the stress field due to architectural defects of the hip joint. The stress state was obtained both for a normal hip in two-leg support and a hip with luxation and lateral dysplasia in one-leg support. The isochromatic fields recorded on plane models of the hip are presented in figure 6 for both cases: a normal hip (figure 6a) and a hip with luxation and dysplasia (figure 6b). A polariscope with circularly polarized white light was used for this analysis. The model of the joint in two-leg support was loaded with a force of 1 kN, representing the resultant force R (between G and F_m) transmitted to the pelvis and applied in the sacrum area, at a scale of 1:2.4.

Using the isochromatic fringe field from figure 6 the variation of the principal stress difference $\sigma_1 - \sigma_2$ on the contour of the cotyloid cavity was plotted for both cases (figure 7).

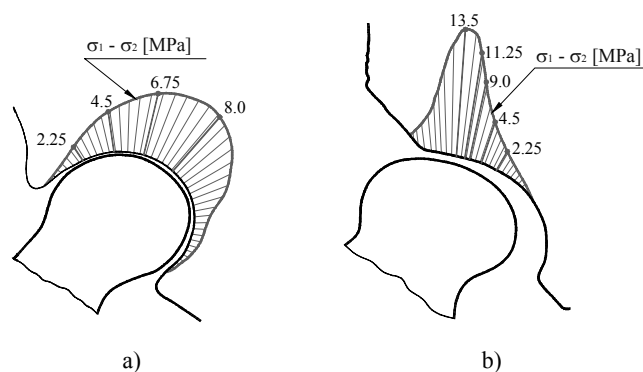
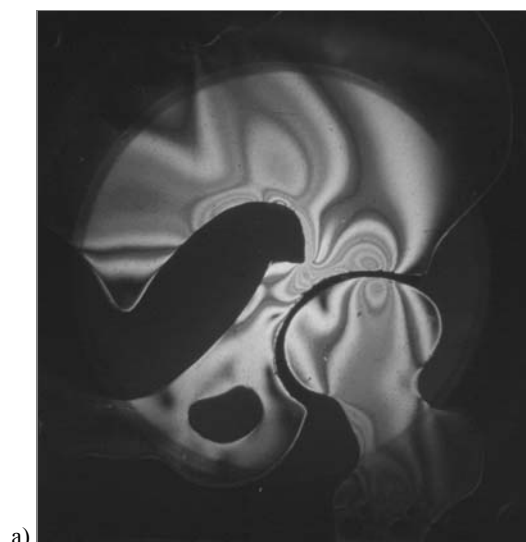


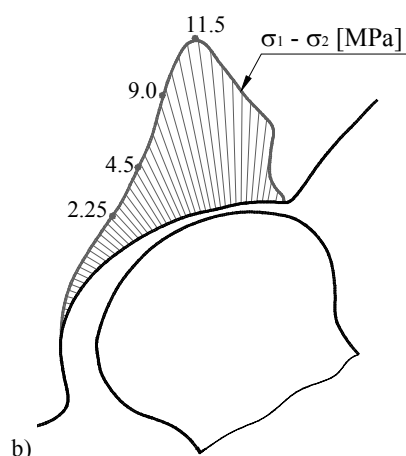
Fig. 7. Variation of the principal stress difference for a normal hip (a), variation of the principal stress difference for a hip with dysplasia (b)

The next study emphasized the improvements in the biomechanics of the hip following the Chiari osteotomy. A plane photoelastic model of the hip, manufactured according to an X-ray picture taken after osteotomy, was studied in a polariscope with circularly polarized light (figure 8a). A load of 800 N (three times smaller than the real force) was applied in the sacrum area, for two-leg support.

The variation of the principal stress difference $\sigma_1 - \sigma_2$ on the surface of the cotyle in this case of osteotomy is presented in figure 8b. The isochromatic fringe field was also obtained from a model manufactured according to an X-ray picture taken two years after a Chiari osteotomy (figure 9a). The variation of the principal stress difference $\sigma_1 - \sigma_2$ in this case is plotted in figure 9b. One can observe that the stress distribution in the latter case tends to be similar to the one characteristic of a normal hip (figure 7a). This better distribution is due to the new, bigger contact zone between the cotyle and femoral head, obtained

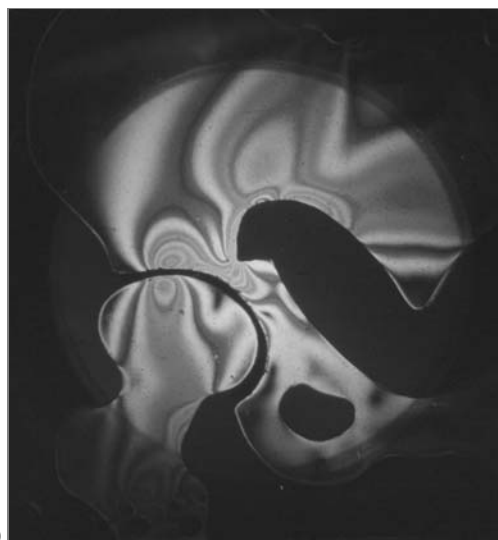


a)

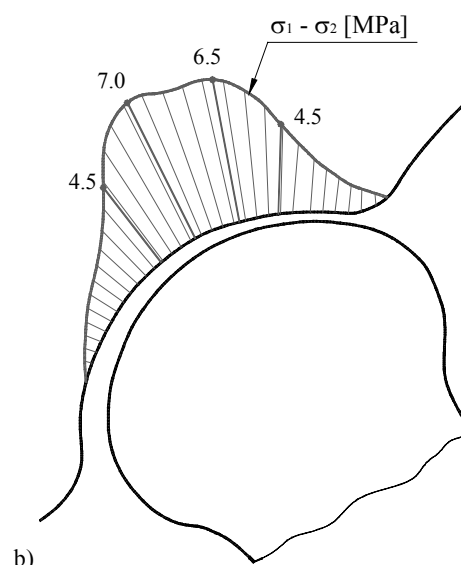


b)

Fig. 8. Isochromatic fringes after the Chiari osteotomy (a), variation of the principal stress difference after the Chiari osteotomy (b)



a)



b)

Fig. 9. Isochromatic fringes two years after the Chiari osteotomy (a), variation of the principal stress difference two years after the Chiari osteotomy (b)

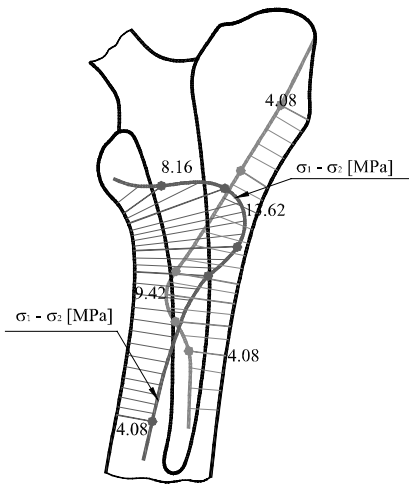
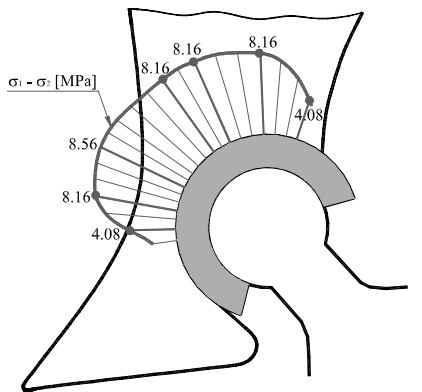
through the recovery and remodelling of the bone tissue after the surgery.

Sometimes the hip arthroplasty used in advanced hip arthrosis presents post-surgery complications due to tardy decementation of the prostheses following the implantation defects [7], [8]. The last experimental study deals with the determination of abnormal stress state due to the malposition of the prosthetic components. A plane model of the prosthetic hip joint was manufactured from two different photoelastic materials: epoxy resin for the bone tissue of the iliac crest and femoral diaphysis (with the elastic constants from the table) and polymethylmethacrylate (PMMA, plexiglas), with lower optical sensitivity, for the cup and femoral piece (having the Young's modulus $E = 2800$ MPa and Poisson's ratio $\nu = 0.37$). The acetabular cup was fixed in the cotyle in

three different positions: normal, vertically displaced and horizontally displaced. A special adhesive (X-60), simulating the cement layer was used. Using the same adhesive, the femoral piece was implanted also in three positions: normal, varus and valgus. Using a system with levers and weights, the models were loaded with a force of 800 N (scale of 1:2.4 of the real force) applied to the top of the cotyle. The photoelastic analysis was done using a polariscope with circularly polarized light (both white and monochromatic).

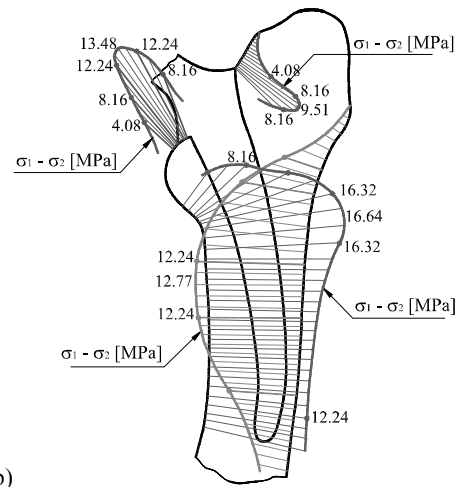
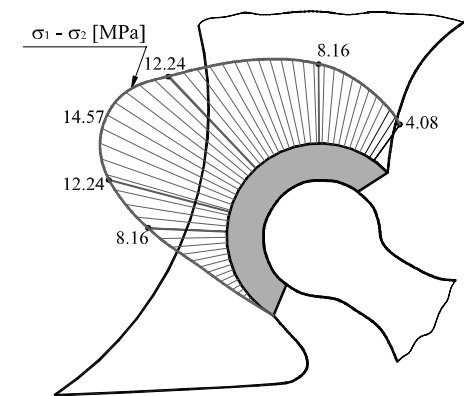
The field of isochromatic fringes recorded in white light for the first analyzed case (cup and femoral piece in a normal position) is shown in figure 10a, while the one for the third case (normal position of the cup and the femoral piece in varus) is presented in figure 11a. Using the information extracted from these fields, the

variation of the principal stress σ_1 for the first case and for the third case (at the interfaces of cup–iliac bone and prosthesis–femoral bone and on the contour of the femur in the epiphyseal-diaphyseal zone) are presented in figures 10b and 11b, respectively.



b)

Fig. 10. Isochromatic fringes in the bone tissue for a normal position (a), variation of the principal stress σ_1 at the interfaces of cup–bone tissue and femoral piece–bone tissue for a normal position of the prosthetic components (b)



b)

Fig. 11. Isochromatic fringes in the femoral diaphysis for a varus implantation of the femoral piece (a), variation of the principal stress σ_1 for a varus implantation of the femoral piece (b)

4. Conclusions

Some important conclusions regarding the contact pressure distribution in some cases of hip joint disorders may be drawn from the photoelastic investigations undertaken. Improvements that may be obtained following the corrective osteotomies in the case of these diseases are also emphasized.

As can be seen in figure 7b, an insufficient coverage of the femoral head due to a deficient development in depth of the cotyloid cavity can be found for a hip with luxation and lateral dysplasia in one-leg support. In this case, cotyle has a contact with femoral head on a reduced surface; as a result, the stress distribution shown in figure 7b has a peak whose value is by 70% greater than the one for a normal hip.

The results of the photoelastic investigations on the Chiari corrective osteotomy (figure 8a) show that, immediately after the operation, the maximum value of the principal stress difference on the surface of the cotyle is 11.5 MPa (by 43.7% greater than for a normal hip and by 17.4% smaller than before osteotomy). With time, after the surgery, a new and larger contact zone is established between the cotyle and femoral head due to the recovery and remodelling of the bone tissue. Consequently, the contact pressure distribution is modified, tending to the normal one, as is shown in figure 9b.

The investigations on the hip prostheses show that the distribution of the principal stress difference $\sigma_1 - \sigma_2$ on the surface of the cotyle is close to the normal one (figure 10b). Greater stresses appear due to the difference between the elastic moduli of the materials (bone and acetabular cup). The shearing stresses at the interface of bone–femoral piece have small concentrations in the area of the femoral spur and internal cortex, along the length of the prosthesis. The results of the research on models with malposition of prosthetic components (figure 11b) revealed that the principal stress difference on the cotyle surface is by 52% greater compared to the normal situation. A greater stress concentration on the diaphysis, at the femoral spur, is noticed (by 32%

greater than in the case of correct implantation). The same phenomenon is observed in the contact area of the prosthesis with the great trochanter, while a diminution of the stresses may be found at the inner cortex along the whole length of the prosthesis. These low values show that the load of the prosthesis–cement assembly in the case of incorrect implantation is greater compared to the normal situation. Thus, the load of the cement layer is higher.

The principal stress difference $\sigma_1 - \sigma_2$ is always twice as large as the maximum shear stress τ_{\max} . Under the shear stress, cement fails leading to a partial decementation of the prosthesis. With time, due to the continuous loading, the total decementation may occur, both at the femoral piece and the acetabular piece. Local micromovements load both the bones and the femoral piece by tilting, leading to a possible failure of the prosthesis due to fatigue.

References

- [1] GARWIN K.L., BOWEN M.K., SALVATI E.A., RANAWAT C.S., *Long-term results of total hip arthroplasty in congenital dislocation and dysplasia of the hip*, J. Bone Joint Surg., 1991, Vol. 73, 1348–1354.
- [2] ANTONESCU D., ILIESCU N., *Metode de calcul și tehnici experimentale de analiza tensiunilor*, [în:] *Biomecanică*, Editura Tehnică, București, 1986.
- [3] PAUWELS F., *Biomechanics of the normal hip and diseased hip – atlas*, Springer-Verlag, Berlin, Heidelberg, New York, 1976.
- [4] DINULESCU I., DENISCHI A., MEDREA O., *Coxartroza*, Editura Publistar, 1997.
- [5] ANTONESCU D., SANDU C., *Acetabulum 3-D Remodeling after Chiari Osteotomy*, 4th Congress of EFORT, Brussels, June 1999.
- [6] KLAUE K., SHERMAN M., PERREN S.M., WALLIN A., LOOSER C., GANZ R., *Extra-articular augmentation for residual hip dysplasia. Radiological assesment after Chiari osteotomies and shelf procedures*, J. Bone Joint Surg., September 1993, Vol. 75-B, No. 5, 750–754.
- [7] DENISCHI A., STĂNCULESCU D., ILIESCU N., *Decimentarea aseptică în artoplastia totală de șold*, [în:] *Biomecanica*, Editura Academiei Române, București, 1989.
- [8] HINTERMANN B., MORSCHER E., *Acetabuloplasty with solid autologus graft for hip dysplasia in total hip replacement of dysplastic or dislocated hip*, Arch. Orthop. Traum. Surg., 1995.