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Experimental methods of stress and strain analysis in orthopaedics biomechanics

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Possibilities of applying several experimental methods to the analysis of displacements, strains and stresses in bone structures and implants are presented. Such methods as photoelasticity, holographic interferometry, speckle photography and strain gauges are described. These techniques are significant in experimental investigations, especially during fast improvement of modern analytical and numerical methods. Experimental methods are indispensable for experimental verifications of boundary conditions in theoretical models. Experimental investigations of real objects and biomechanical models were carried out.

Key words: biomechanics, photoelasticity, holographic interferometry, speckle photography, ESPI, Moiré method, strain gauges, hip joint, lumbar spine, knee joint, jaw, stabilisers of endoprosthesis

1. Introduction

Development of modern numerical methods and computational techniques in the field of biomechanics allows us to solve highly complex problems encountered in the assessment of the strength and reliability of bone structures and implants. But they usually require boundary conditions determined experimentally or courses of the involved phenomena. An experimental analysis of tissue structures and implants, which includes empirical activities aimed at determining the relationships between the quantities that characterise a given object or process, can be divided into three basic stages: the design of an experiment, the realisation of the experiment and the analysis of the results obtained. Depending on the goal of an investigation, e.g. the validation of hypotheses, assumptions or mathematical models or the identification of a model of an investigated object, the particular stages of an experiment are subject to modification. The following stages can be distinguished in identification: modelling, an experiment, the estimation of parameters and the validation of the model [20], [27], [28].

Presently, next to the numerical methods, the experimental methods, which make use of effect of polarised and coherent light, are often used in the investigation of biomechanical structures [15]. These non-destructive testing methods enable us to examine various biomechanical objects like femur bone with endoprosthesis and in this way we avoid influence of sensors on measurement results. Moreover, optical methods combined with computational techniques allow making both qualitative and quantitative analyses of displacements and strains' distributions. On the basis of the fringe patterns obtained investigators can deduce the nature of the phenomenon occurring in the object. In biomechanical studies we usually deal with orthotic structures and point methods are unsuitable. The next important fact is that we can measure the particular effect in the same time.

The combination of experimental methods with the capacities of modern computers resulted in the creation of tools with almost limitless possibilities in the field of stress and strain analysis [7], [17], [20]. Hybrid techniques (figure 1) make it possible to model more accurately and realistically physical processes occurring in biomechanical objects. They allow us, for example, to assess the effect of such material properties as heterogeneity and anisotropy, viscoelasticity and viscoplasticity, the variation of stresses and strains in time under loading and macro- and micromaterial constants on the state of stress and strain in bone structures [18].

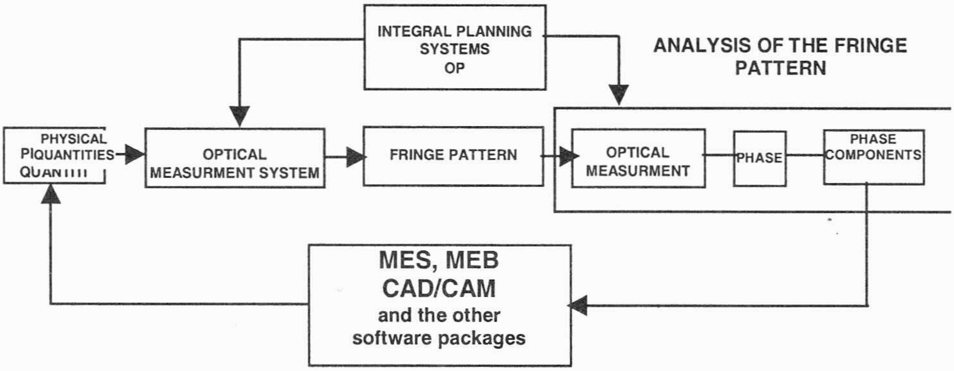

Fig. 1. An application of the hybrid experimental system in analysis of stress distribution using optical methods [18]

Methods of experimental investigation of stresses and strains in anatomical parts of the human body have become established in biomechanics [1], [7] which in recent years has concentrated on finding out the causes of diseases of man's osteoarticular system and on developing optimal methods of treating them. Usually the most heavily loaded elements such as the vertebral column, the hip joint and the lower extremities are investigated.

Physical and numerical models should render possibly faithfully a real object and an experimenter must determine the effect of any simplifications on the results obtained. Generally it is impossible to model the ligamentous-muscular apparatus and the nervous system in their whole complexity and the biological and biomechanical factors involved in the human osteoarticular system. The analysis of stresses and strains in human anatomical structures and implants by calculation methods often runs into difficulties because of the complexity of the objects investigated. The complex structure, functions and state of loading are the reason that the calculation models adopted, including numerical ones, must be verified experimentally. If osseous implants are used, it is vital that proper strain and stress relations are maintained in order to ensure the proper interaction between the bone and the implant. Experimental methods applied to real objects or their models have become indispensable tools of identification of such objects.

The methods presented in this paper are used to identify biomechanical phenomena occurring in bone structures and in all implants and to shape them optimally taking into account the limit strength or the strain continuity. Designs in this case are evaluated on the basis of stress, strain and displacement distributions determined by means of various experimental methods. We focus our attention on such methods as photoelasticity, holographic interferometry, interferometry and the electronic speckle interferometry technique, speckle photography, the moiré technique, strain gauges and hybrid methods. The methods enable both qualitative and quantitative analyses of stresses, strains or displacements in the biomechanical object investigated. Optical measurement methods are particularly useful since measurement does not involve touching; moreover, they offer possibilities of both qualitative and quantitative point and field analyses. The results obtained, related to implant design features, are highly visual. Right at the beginning it is possible to evaluate the correctness of an implant design and thus the whole-investigated field can be analysed. Then by changing the design features of an artificial joint it is possible to obtain optimal, in a designer's opinion, stress or strain distributions. The model's geometric features can be modified until the sought effect, e.g. a minimal element weight for a uniform distribution of possibly minimum stresses, is achieved.

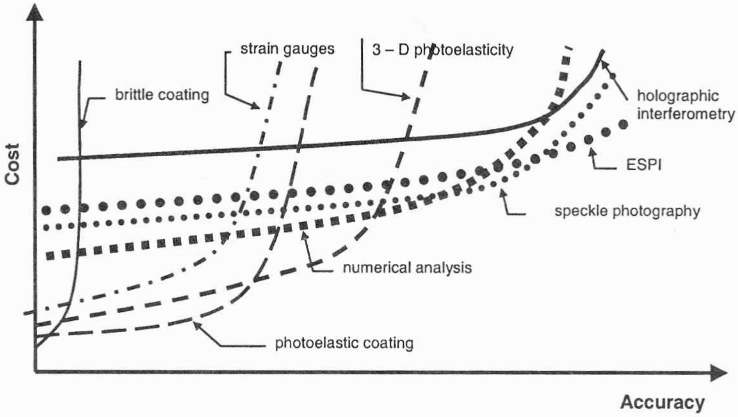

Fig. 2. Accuracy of different experimental methods
and numerical analysis versus their total costs [6 adopted]

The methods considered differ in their accuracy. One of the most sensitive measurement methods is holographic interferometry, which allows us to determine the displacements in the order of 150–200 nm. Less sensitive (by an order of magnitude) is speckle photography followed by the photoelastic method, but the latter allows us best to optimise the shape of implants taking into account the stress and strain distributions determined.

The relative costs of developing and testing a design should be carefully considered in order to select an appropriate analysis method. The costs of calculation methods should be compared with those of experimental methods, and the goal to be achieved must be taken into account (figure 2). A selection of a research method should also be made on the basis of the relative costs which are due to the complexity of the object investigated [7].

2. Photoelastic methods

The photoelastic methods ([1], [8], [14], [21] and [29]) are applied in stress and strain measuring techniques using temporary double refraction which occurs in some materials (e.g. epoxy resins, urethane elastomers, etc.). Photoelasticity is usually used to investigate the models of real objects, but it is possible to make measurements of the models in which there is a two- or three-dimensional state of stress. In a full measurement cycle, a qualitative and quantitative assessment of the stress distribution in the whole-investigated field can be made, the trajectories of principal stresses can be determined and stress concentrations can be indicated. Photoelastic investigations can be conducted under static and dynamic load conditions. Photoelasticity is the only experimental method that enables the analysis of a three-dimensional state of stress.

Photoelasticity is used mainly to investigate models of objects and measurements are typically made by shining through the model investigated. MILCH (1940) was one of the first researchers who applied photoelasticity to orthopaedics to analyse stresses in the upper part of a femur. Photoelasticity has been applied to investigate stress distributions in models of the spine, the hip joint, the knee joint and the tarsal joint [1], [7], [8], [10], [21], [29].

2.1. Application of photoelasticity in three-dimensional stress analysis in lumbar spine

The vertebral column constitutes the most primary and essential component of man's skeletal system which performs the following basic functions: protects the spinal cord, serves as the motor system and provides support to the body [1]. The spine, because of its complex and peculiar structure, fulfils only the first function properly. Because of these multiple functions the spine is subject to considerable loading even under physiological conditions and it is often overloaded. The lumbar part of the spinal column is one of the most important weight-bearing element in human body and plays a critical role in the carrying of loads. Overloading means the state in which the physical strength of the tissues has been exceeded due to the forces resulting from the carrying of loads. Degenerative changes caused by overloading take place in the lower spine, they affect the intervertebral discs, the ligaments and the lateral surfaces of the vertebrae. The mechanism of overload damage to spine elements has not been explained fully yet. The predominant view is that mechanical factors such as load distributions, the geometry, shape and physical properties of the spine structures as well as stress and strain distributions contribute greatly to the overloading of the spine.

The goal of the investigations presented below was a comparative analysis of the three-dimensional state of stress in the lumbar spine under different load conditions. The stress freezing technique was used in the investigations [1], [21]. In order to match better the mechanical properties of the bone under real conditions, model of lumbar spine consisted of different materials: cortical and spongy bone of the vertebrae was made of epoxy resin, while the disc between vertebrae based on silicon. The spine model was made on a scale of 1:1 (figure 3a).

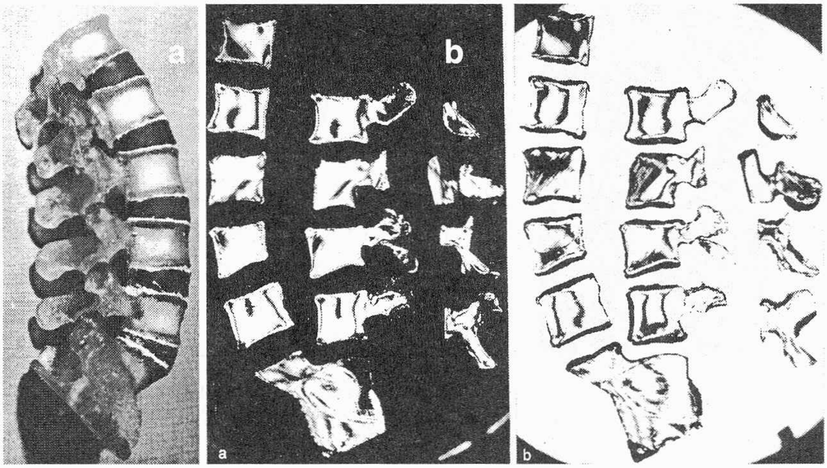

Fig. 3. Three-dimensional model of lumbar spine (a), exemplary distributions of full and half-isochromatic patterns in middle slice of lumbar spine (b) [1]

In order to render the complexity of the state of loading in the lumbar spine possibly well, a special loading system was constructed. Exemplary pictures of full and half-isochromatic patterns for sample from the middle part of three-dimensional models of the lumbar spine are shown in figure 3b.

The results of the studies enable us to define reliable hypothesis explaining formation of the overloading changes in the lumbar spine, especially in the L4–L5 vertebrae. The impact of the lumbar lordosis and inclination of the sacrum bone were determined to be responsible for spondylolisthesis phenomenon in lumbar vertebra arches.

2.2. Application of photoelastic coating onto human femur with hip stem

The photoelastic [1], [8], [9], [13] coating is the most versatile method, which enables full-field strain measurements of real structures under different loads' conditions, e.g. static and dynamic. Typically, optically sensitive material is applied onto the surface of an object made of the original material. This particular experimental method is suitable for laboratory or field measurements, using lightweight portable equipment. It is possible to make measurements in such a way that a ray of polarised light passes twice through a layer of optically sensitive material (the reflected light technique). Using that method we are able to observe and measure the assembly stresses as mating components are joined. Besides, the residual stresses residing in a material as a result of the manufacturing process can be detected. Photoelastic coating is useful in detecting yielding, since any permanent deformations that occur in the part or structure will be displayed in the coating after removal of the test forces. This optical method has been successfully used in biomechanical research since the 30s. An exemplary result of practical application of the photoelastic coating is shown in figure 4.

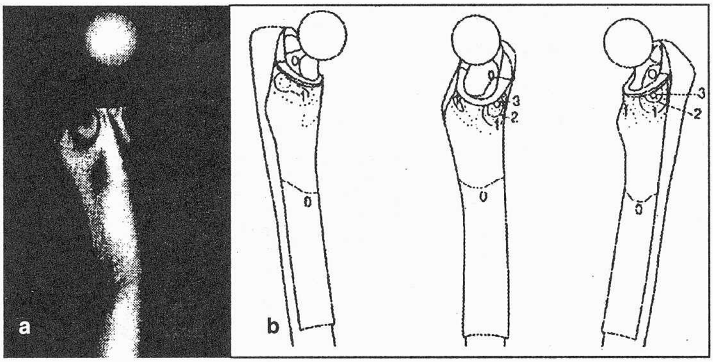

Fig. 4. Femur bone with a photoelastic layer: a) isochromatics pattern, b) distributions of the isochromatics in different parts of bone [9]

Application of the photoelastic coating in an original femur bone with endoprosthesis enables us to determine the strain distributions under different load conditions and to estimate the different kind of implantation method. The results obtained are useful in optimisation relationships between bone and implant in the hip joint.

3. Application of holographic interferometry

Holographic interferometry combines the measurement of small displacements with holographic image recording. At the moment this method ensures the highest sensitivity of measurement, it is universally applicable and it enables both qualitative and quantitative analysis of whole fields investigated (even large ones). Another advantage is that a real object can be measured without touching it [1], [6], [11], [21], [23], [26].

Holographic interferometry is based on the principle of double recording of the image of an object investigated and it is used either to measure small displacements of points on the surface of a body subjected to all kinds of loads, e.g. mechanical loads, thermal loads, vibrations, or to study mechanisms of failure of structural elements. The obtained information about the object's surface is used to calculate stress and strain values by differentiating the displacement field and taking into account the physical properties of an object investigated.

3.1. Strain tensor of human lumbar vertebrae

Loads acting on the vertebral body, the intervertebral junctions and the ligamentous-muscular elements contribute largely to deformities and dysfunction of the spine. The spine under such loads assumes an appropriate shape affecting the spine's curvatures, e.g. in the sagittal plane. The analyses of stresses, strains and displacements of the vertebra's elements in spondylopathy induced by overloading may shed some light on the pathological mechanism. In recent years holographic interferometry has been increasingly used to analyse deformations of bone elements [1], [3], [22].

Using the traditional holographic interferometry it is possible to develop a complete method for measuring three components of displacements in the area of human lumbar vertebrae.

The displacement measured in three independent, not planar directions gives a complete information about the displacement. Knowing the mutual position of these directions and their orientations in relation to an arbitrary Cartesian system connected to the system analysed it is possible to describe the displacements in the orthogonal x, y, z-system [21]. In order to fully describe the displacements we need to record three holographic interferograms, each in the different directions. Once it is done we can calculate displacement components in directions of sensitivity of those interferograms.

The system is based on a traditional measurement system used in holographic interferometry in one direction. The system was tested and the best position, taking into account practical and computational matters, was chosen [3].

In this configuration the mutual position of the sensitivity vectors **K**1, **K**2, **K**3 and Cartesian system x, y, z are as presented below (figure 5).

This method was applied here to study a natural lumbar vertebra in different biomechanical situations [1], [3]. The purpose of the analysis was to determine strain and stress tensor of the vertebrae arch. Vertebrae loads were selected according to the functional analysis of lumbar vertebrae using equations of equilibrium (Stotte's model) [1]. During the analysis mutual influences of vertebrae through vertebrae body surface and the influence of muscle and ligament forces acting on spinous process, which caused the displacements, were modelled. The investigations were conducted under loads simulating the compression of the vertebral body and the bending of the vertebral arch (the loading of the spinous processes). An exemplary interferogram of the vertebral arch when the spinous process is loaded with the force of 4 N is shown in figure 6.

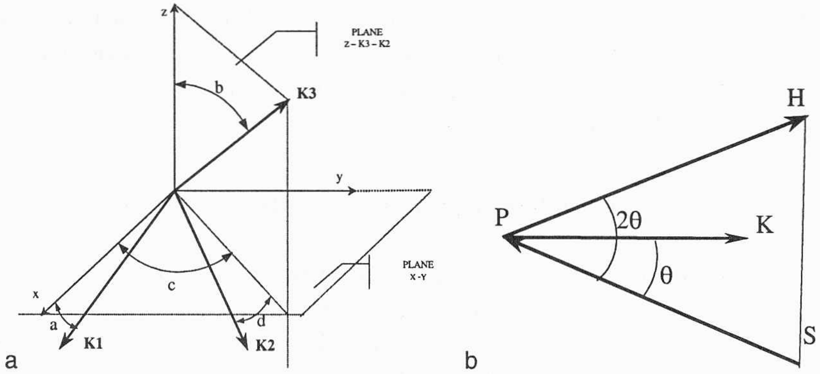

Fig. 5. Mutual position of **K**1, **K**2, **K**3 vectors and *x*, *y*, *z* (a), sensitivity vector position (**K**) in reference to holographic plate (H) and the lens (S) (b) [3]

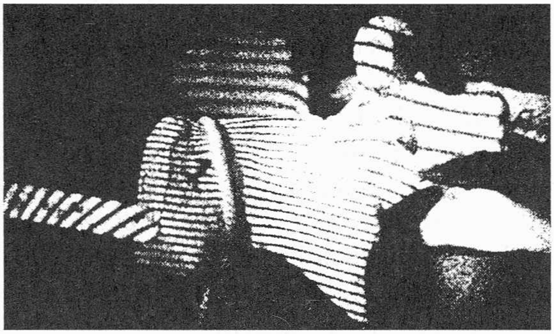

Fig. 6. Interferogram of the vertebral arch

A diagram of the cross-section for which the values of the displacement components and the values of the strain and stress tensor components have been determined is shown in figure 6.

After interferograms of the three spatially situated holograms were recorded it became possible to determine the displacement components (*dx*, *dy*, *dz*) and then the strain components. When values of the material constants were assumed, the stress distributions were determined. Exemplary distributions of the strains εy, εz, γyz for the middle cross-section of pedicle B–B (according to figure 7a) are presented in figure 7b. One of the graphs is for flexural loads acting on the spinous process (simulation of bending forward), while the other – for loads compressing the vertebral body.

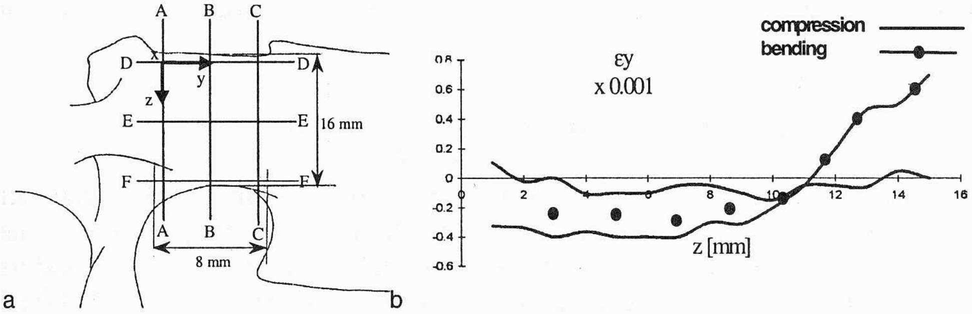

Fig. 7. A diagram of the cross-section (a), an exemplary distributions of the strains εy, εz, γyz for the middle cross-section of pedicle B–B (b) [3]

The research method developed, involving the determination of three displacement components by means of the holographic interferometry technique, makes it possible to determine very small values of displacement and stress components. The method can be applied to the examination of real objects, i.e. vertebra cadaver specimens. Three-dimensional holographic interferometry is particularly suitable for biomechanical studies, since the displacement of a real object is measured and the measurement does not involve touching. Due to high sensitivity of the method we can use it to analyse the changes in the surface even when the displacements are very small. The method can be used to determine the tensor of strain or stress of complex objects such as bone with implants to assume the boundary conditions in numerical computations as well. Concerning all these remarks we can state that the method proposed is especially useful in analysing small biomechanical elements, straining in a complex way, like vertebrae, arm and lower extremities. The high cost of experiments and difficulties in adjusting the system are the main disadvantages of this particular optical method.

The strain and stress distributions in the vertebral arch vary significantly depending on the applied scheme of loading. Thus one can say that the vertebral arch clearly responds to the character of the vertebra's work and to the kind of loading. Because of the complex structure of the vertebra (sharp variations in its cross-section and mechanical properties), the strain and stress distributions in the regions analysed have complicated forms. The results prove that the displacements, stress and strain distributions of the vertebrae arch under variable loads of spinous process are very irregular.

The experiment has proved that holographic interferometry can be used for simultaneous measurements of three components of the displacements of the surface examined. Determining the displacements allows calculating strain and stress and therefore strain or stress tensor of surface can be found.

The strain tensor in the lumbar spine obtained by using holographic interferometry and three-dimensional state of stress described in point 2.1 enable us to develop hypothesis about fatigue in the vertebral arch connected with abnormal load transfer in the lumbar spine.

3.2. Studies of the displacement of the human jaw

Fractures of the human jaw are one of the most common injuries of the facial part of cranium [30]. Different types of artificial plates have a practical application in the treatment of this injury. Type of fracture, the geometrical features of the plate and its mechanical properties have a decisive influence on the quality of junction and final results of the clinical treatment.

The aim of this paper was to determine the displacement and strain distribution in the human jaw during biting before and after implantation. The epoxy resin model of the jaw (figure 8) with simulated typical fracture was analysed using the holographic interferometry method.

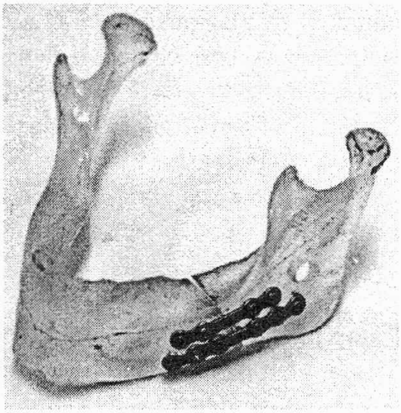

Fig. 8. Model of the jaw with the plates [30]

Two artificial plates made of titanium alloy combined the jaw fracture. The applied load system reflected anatomical and biomechanical conditions. In this particular investigations, three kinds of load were considered: first force was applied onto the frontal incisors, and separately onto the left and the right canine tooth (figure 9).

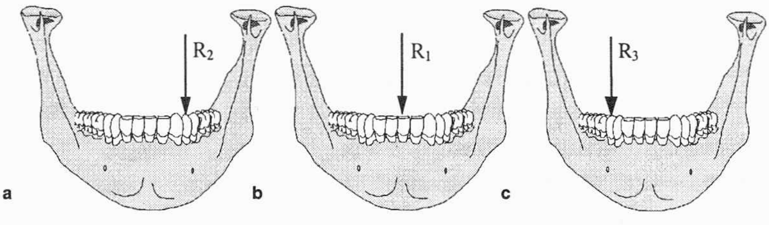

Fig. 9. Schemes of the load systems applied [30]

On the basis of series interferograms it was possible to determine the value of the displacement in particular points (figure 10b) at the fracture boundary on the left and the right fractions of jaw.

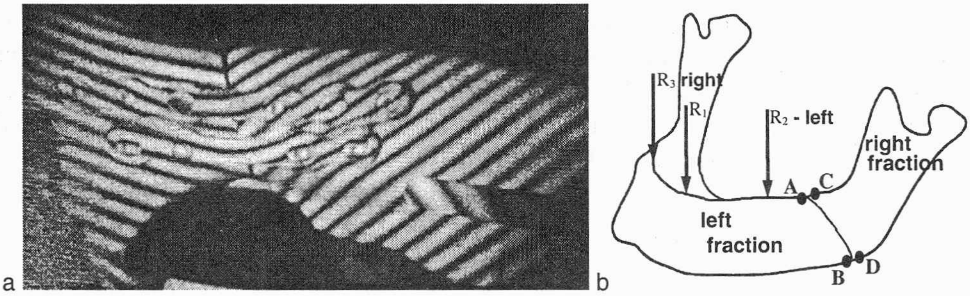

Fig. 10. An exemplary interferogram of jaw with two plates (a), points at the boundary of fracture in which the values of displacements were measured (b) [30]

The upper boundary of the displacements of the jaw fractions in the gap of fracture is not determined exactly. On the basis of clinical observations it is assumed that displacements of fractions could not exceed 1 mm. The results obtained show that this system of stabilisation, which is often used in clinical practice, guarantees a proper stabilisation of bone fractions. These results can be used in the future investigations to vary geometric features of the plates.

Non-destructive testing method (fulfilling analysis of the object) enable us to investigate both different kinds of plates used in jaw osteosynthesis and different kind of load condition. On the basis of the results presented above a new jaw plate will be designed.

4. Application of speckle photography

Speckle photography [1], [6], [12], [27], similarly as holography, is a non-touching measurement technique which is used to analyse displacements in a direction parallel to the surface of an object and to measure the deflection and the angular displacement of a normal to the surface of investigated object. This technique makes use of the so-called speckle effect associated with the diffusion of coherent light by an optically uneven surface. In the case considered, the laser light rays, while illuminating an area investigated, are reflected and dissipated by the bone's surface irregularities. By interfering with one another they form a pattern of light and dark speckle situated in front of the dissipating surface. There is a close relationship between the pattern of speckles and the particular points on the surface. As the illuminated area of the bone displaces so do the particular speckles. By recording the pattern of speckles, using the double exposure technique, before and after loading a specklegram is obtained.

The main advantage of speckle photography technique is the possibility of simultaneous recording in a whole measurement field whose dimensions are limited only by technical capacities. Practically, it is possible to record displacements in the whole-investigated area during one exposure. This is particularly important if one takes into account the high variability of the mechanical properties of the bone and thus the variability of the distribution of its deformations and of the displacement of points lying on its surface. Additionally this non-contact method does not introduce errors, associated with the direct influence of the measurement path on the object investigated, into the quantities measured [6], [21].

4.1. Analysis of displacement of knee joint

In the case of advanced disturbance of lower limb geometry with varus deformity of the knee, total two- or three-dimensional alloplasty is commonly employed as a treatment [1], [4]. If there are general or local contradictions, even in extensive arthrosis of the knee with varus position and lateral or antelateral instability, interligamentous popliteal osteotomy (Coventry) may be performed. The difference between the costs of the two solutions is also of significant importance. Clinical studies conducted for several years now at the Orthopaedic Department of the Specialistic Rehabilitation Health Care Centre in Wrocław prove that it is necessary to modify the Coventry technique. On the basis of the clinical studies and studies of knee joint biomechanics, a procedure was developed for performing popliteal osteotomy in patients in whom the shape of whole lower limb contributes to the subluxation (defined as a distance between the limb's mechanical axis and the joint's anatomic centre at the level of the articular space) of the knee joint when the traditional operative procedure is employed. Therefore, the main aim of these investigations was to verify experimentally the operative procedure proposed. The investigations covered comparative studies of the knee joint in four conditions: anatomically and physiologically normal joint (stage I), varus joint (stage II), joint after Coventry popliteal osteotomy correction (stage III), and the joint after new variety of the Coventry procedure (stage IV).

Based on the investigations of the displacement of points on the bone's surface, the model of the knee joint was constructed from real autopsy preparations – homogenous bones dissected free and suitably prepared. The investigations were conducted only under static conditions. In the investigations, symmetric standing on the two lower limbs at full extension and asymmetric standing on one lower limb at full extension were reproduced.

The interaction between the articular surfaces was evaluated by measuring the frontal plane displacements of points lying near the articular space which was done by speckle photography. Displacements in the region of the articular space were measured along a line parallel to it (figure 11). Results of the experimental investigations are shown in figure 13.

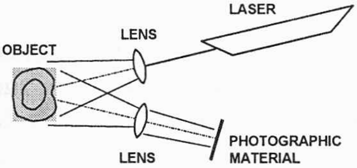

Fig. 11. Optical arrangement for recording of specklegrams

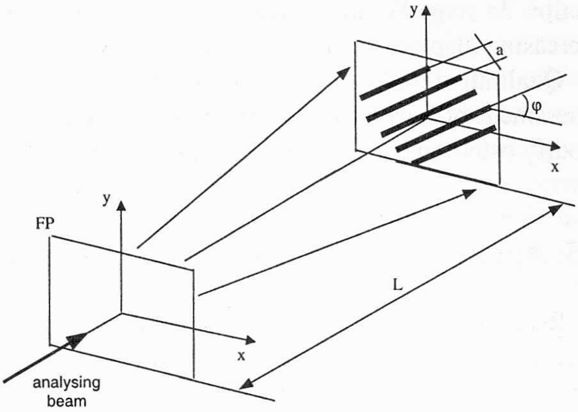

Fig. 12. Optical arrangement for reconstruction of the specklegram and measurement of the distance between fringes and the angle of inclination φ [1]

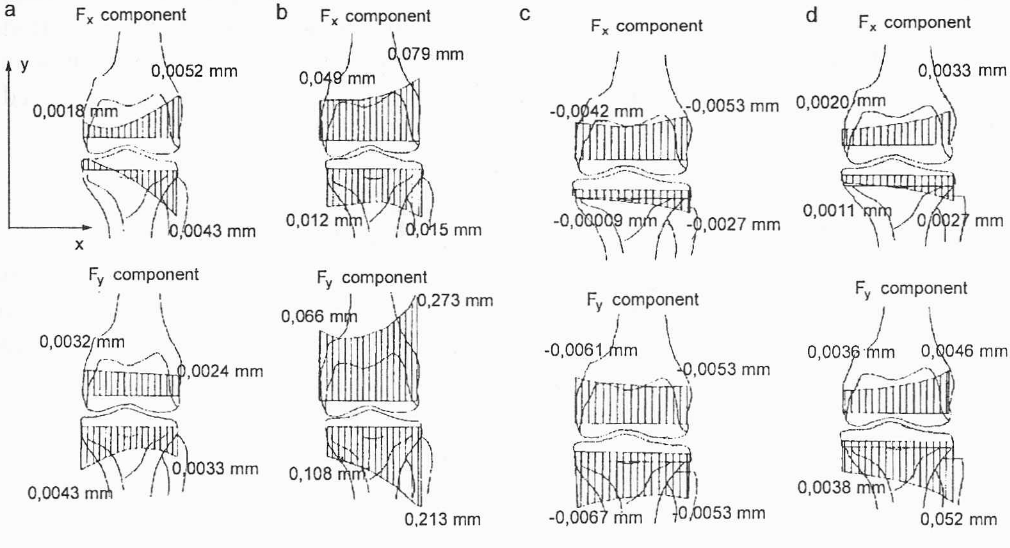

Fig. 13. Displacements measured in coronal plane:
a) stage I, b) stage II, c) stage III, d) stage IV [4]

In stage I, displacements in the frontal plane indicate a very stable position of the knee joint. It is observed that vectors of frontal plane components of displacement on lateral condyle of tibia are directed laterally, and vectors on medial condyle of tibia are directed medially. In stage II, every displacement vector on the tibia is directed laterally – it is the effect of increasing varus deformity under the load applied. In stage III, displacement vector on the tibia condyles is directed medially as a result of correction. In stage IV, the distribution of displacements is similar to that in stage III, but increasing displacement is evident.

Qualitative and quantitative analyses of the femur and tibia bones contributed to assessment of knee joint deformation. Thanks to these results we could work out and modify osteotomies of the knee joint used in the surgical treatments.

5. Application of ESPI – electronic speckle pattern interferometry

Recently significant [19], [29] improvements of laser Doppler techniques gained interest in bone analysis. Laser speckle interferometry ESPI allows the full field and three-dimensional measurement of deformation and strain on complex surfaces. In electronic speckle pattern interferometry (ESPI) (figure 14), a speckle pattern is formed by illuminating the surface of the object to be tested with laser light. This speckle pattern is imaged onto a CCD array where it is allowed to interfere with a reference wave, which may, or may not, be speckled. The resultant speckle pattern is then transferred to a frame grabber on board of a computer where it is issued in memory and displayed. When the object has been deformed or displaced, the resultant speckle pattern changes due to the change in path difference between the wavefront from the surface and the reference wave. This second resultant speckle pattern is transferred to the computer and subtracted from, or added to, the previously stored pattern and the result is rectified.

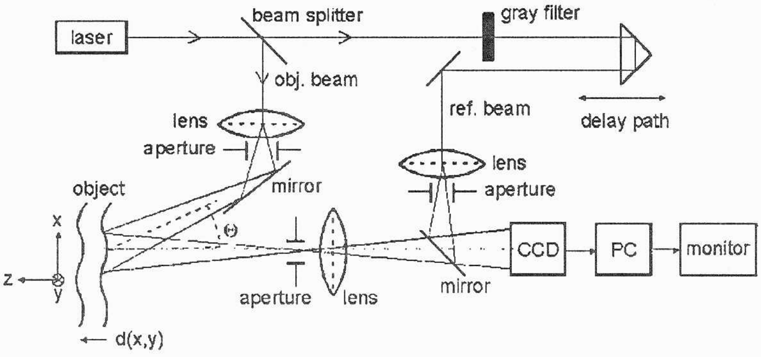

Fig. 14. Diagram of a typical optical configuration [29]

The resulting interferogram is then displayed on the monitor as a pattern of dark and bright fringes, called correlation fringes, as the fringes are produced by correlating the intensities of the resultant speckle patterns taken before and after displacement. It is possible to grab continuously frames, while a deformation is occurring, and subtract them in succession from the first speckle pattern, in real-time. In this way it is possible to observe the real time formation and the progressive changes of the fringe pattern related to the deformation of the surface.

The fringe patterns obtained by the ESPI technique represent contours of equal displacement. The spacing of the fringes is inversely proportional to the displacement and, in in-plane systems, the fringes are aligned perpendicularly to the direction of the displacement. Two consecutive dark or bright fringes represent a displacement whose exact value depends on the wavelength of the light used and the geometrical setup of the ESPI system. This value of this displacement is called the fringe sensitivity term. The displacement between two points can be easily calculated by counting simply the number of fringes between those points and multiplying the result by the fringe sensitivity term. This can be a slow and tedious process when analysing complex fringe patterns and this technique is associated with a relatively large error. However, with high-speed digital computers the fringes can be quickly processed using automatic fringe analysis and precision phase measuring techniques to provide accurate quantitative results. The most common techniques for this interferogram interpretation are the Fourier transform and phase-shifting methods [19]. ESPI enables us to determine the value of displacements both in vivo and in vitro conditions under different state of loading: statical or dynamical.

Application of the ESPI in our laboratory allows investigations of the strain wave propagation in bone structure. It would be possible to estimate how density and damping of the bone preparation and kind of an artificial implant impact on wave dumping in the bone.

6. Application of moiré method

It is well known that optical non-destructive testing methods are highly sensitive and allow a full-field analysis of the area investigated without any need for physical contact with the surface. They can sometimes provide information where the other experimental techniques fail or cannot be applied [1], [7], [27].

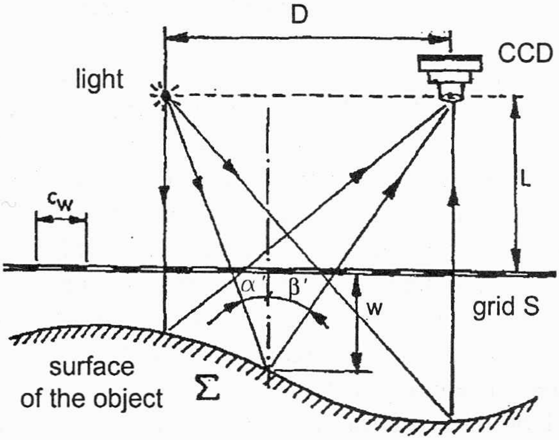

Fig. 15. Typical configuration of the measuring system in shading moiré [1]

The moiré method, known as an optical incoherent technique, is used to determine the shape or displacements' distributions at the objects. In such investigations, usually projection and shading moiré are used. In general, the term *moiré* denotes a phenomenon of interference of two regular patterns in the form of a series of parallel or crossed lines (figure 15) [21]. In optics, the effect arises when two gratings or grids are placed in proximity with one another with a small angle between grating lines. The resulting pattern has a lower spatial frequency than those of the individual gratings, the exact value depending on the angle between the lines of two gratings.

The non-destructive testing methods, which can enable us to estimate the posture's faults and spine's diseases, have been searched in medical diagnostic recently. The moiré method is an optical, incoherent technique used in analysis of the displacement field or the shape investigations and it turns out to be one of the best in this particular case. It allows us to determine the shape of the human body and to measure in-plane the displacements of the back surface (figure 16).

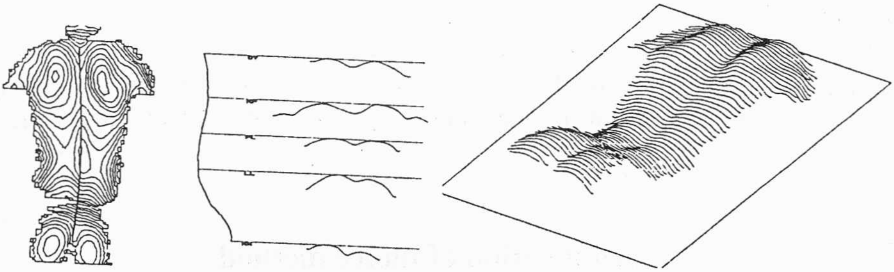

Fig. 16. Graphical presentations the results of the deformations of the muscle–skeletal system in the human back [1]

7. Application of strain gauges

Extensometry [1], [7], [21], [25] deals with methods of measuring deformations of solid bodies. Changes in the length of segments of straight lines connecting points on a body and changes in the angles between the segments reflect the body's deformations. Extensometers are the instruments, which exploit the phenomenon that a conductor's resistance changes as it expands or contracts to measure such deformations. They are precision instruments characterised by high sensitivity, a slight measuring error and measurement repeatability. Extensometers that are used to investigate stresses and strains in structural elements can be divided into two groups: electric extensometers and mechanical extensometers. An appropriate type of an extensometer is selected depending on the measurement conditions and requirements associated with the kind of a material, the shape of a structural element and the kind of loading.

7.1. Experimental analysis of external fixator for femoral bone elongation

The interest in the external fixation system for limbs developed by Ilizarov has been growing in the last decade [1], [2], [16]. This is above all due to the high, in comparison with other fixators, effectiveness of treatment by the Ilizarov fixator of, e.g. complicated fractures of long bones, pseudarthrosis and limb axis correction or shortening. This high efficacy of the Ilizarov fixator results from, among other thing, its modular design that allows one to create numerous configurations of the fixator and to modify its spatial arrangement during treatment depending on the needs [5]. Another advantage is that the fixator's mechanical properties are conducive to the preservation of the optimal biomechanical conditions at the place of the joint of the bone fragments. The Ilizarov fixator is a flexible stabilizer. This means that the load acting on the bone is carried both by the fixator's structure and the place of the join of the bone fragments, which ensures the axial dynamisation of the latter.

The elongation of the lower limbs is one of more interesting, but highly complex – both in the clinical and mechanical aspects – cases of the application of the Ilizarov fixator. Though the clinical experience in the elongation of the lower extremities by means of the Ilizarov fixator is long, many disturbances and complications still frequently beset this process. This is particularly the case when the lower limbs are elongated in the thigh sections where complex conditions of a load acting on the femoral bone in the hip joint occur in usually strongly developed muscles' groups surrounding the thigh being elongated. The failures in the elongation are above all due to the still unexplained mechanisms of the effect of the fixator on the limb being elongated and conversely, the effect of the soft tissue surrounding the treated bone on the fixator's structure.

The aim of this paper was to analyse the stability of the system formed by the Ilizarov fixator and the thigh being elongated [1], [2]. The goal of these studies was to define the conditions of the load acting on the particular distance rods of the Ilizarov fixator and its changes during the elongation of the lower limbs in the thigh section. The tests were conducted in the distance rods of the stabilizer mounted on patients undergoing thigh elongation under clinical conditions. The forces were measured in all distance rods connecting the rings between which the bone's shaft had been cut. It was presumed that knowing the load pattern for the particular rods and their distribution around the bone being elongated, it would be possible to determine which groups of muscles acted stronger and which weaker on the system: the bone fragments–the Ilizarov fixator and how these actions changed during the whole process of elongation.

Specially adapted extensometer converters built into the distance rods of fixator mounted on patients undergoing thigh elongation were used for the measurement of the forces acting in the distance rods (figure 17).

The measurement covered ten cases of thigh elongation by the Ilizarov fixator. Measurements were made once a day at a fixed time, immediately before and after the increase in the length of a distance rod.

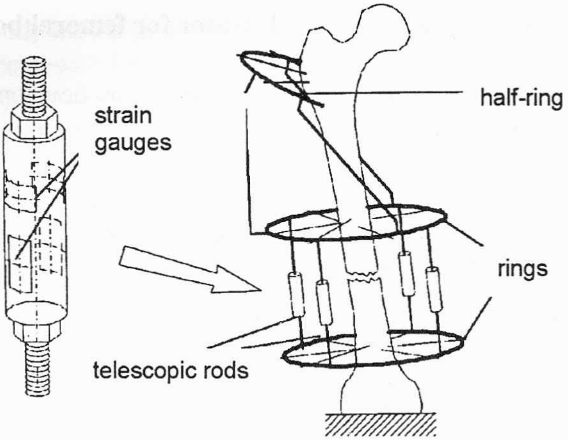

Fig. 17. Force transducers and their localisation in distance rods of external fixator [1], [2]

Figure 18 shows typical variations in distance rod load as a function of time recorded for selected cases. An analysis of the results recorded for the particular case shows that in most of them, the increments of forces in neighbouring rods are similar both in their character and in the variation of their values. The investigations have demonstrated that the stability of the system: the Ilizarov fixator–the thigh being elongated, measured in values of the transverse displacements of the bone fragments, is a function of both the mechanical properties of the adopted fixator structure and the distribution of the forces acting on this system.

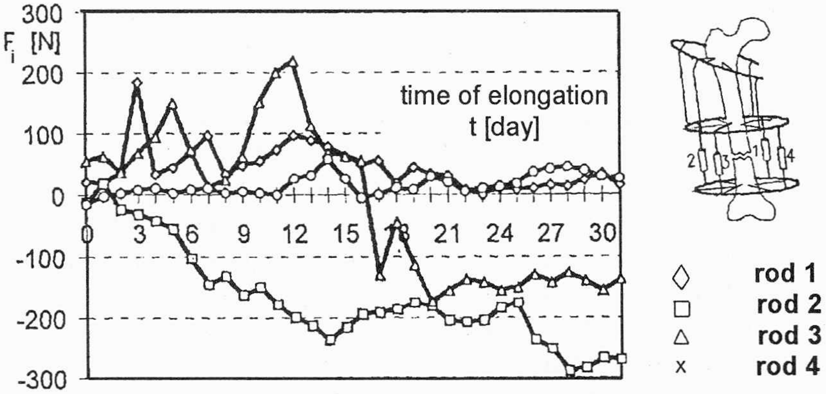

Fig. 18. Distraction load measured in function of time: rate of elongation: 4×0.25 mm per day [1], [2]

The clinical studies allowed determining the distribution of loads in the particular distance rods of the Ilizarov fixator and the variation of the loads as a function of the elongation time. The clinically developed and applied measuring method allows one to control continuously the correctness of the limb elongation by analysing the conditions of the loading of the particular rods of the Ilizarov fixator and the changes of these loads as a function of the elongation time.

The studies conducted under clinical conditions have indicated that the preliminary assessment of the patient's physical condition – above all the degree to which the muscles surrounding the bone to be elongated are developed and trained, whether scars and pathological changes are present – is of major importance. When the mechanical properties of the soft tissue have been taken into account the effect of the optimal spatial configuration of the fixator can be selected for the particular course of treatment. This means that in a clinical practice the goal adopted will be achieved in the shortest time without any complications.

8. Conclusions

The experimental methods, which are often used in analysis of the displacements and the stress distribution of the elements of human body, have a steady position in biomechanical investigations. At the present the biomechanical studies are carried out in many scientific centres all over the world, in order to explain the reasons for orthopaedics diseases and to work out the optimal method of treating human skeletal system. The scientific research frequently concerns one of the most loaded elements in human body like spine, hip joint and lower extremities. The experimental and numerical studies are mainly carried out on models and under clinical conditions. The results of these investigations help to explain and to understand the formation of the degeneration changes in the skeletal system and to elaborate efficient treatment methods.

In biomechanics, we focus our attention on two most important problems: the goal of the investigation and the method which enables us to achieve this goal. Physical and numerical models should be original and should allow us to estimate the influence of simplifications, which are made, on final results. Usually in this kind of research it is impossible to show the complexity of muscle–ligament system, nervous system, biological and biomechanical factors which are involved in the skeletal–joint system of human body. Even investigations, which are carried out on specimens, are also burdened with these limitations. In anatomical specimen, one of the most important limitation is time elapsing from sampling to testing. As it is mentioned above, the results of experimental studies take advantage of verification of theoretical models. Besides, these results can confirm and complete the clinical observations. It could not be possible to determine the patomechanism of some diseases nor to estimate the treatment method applied, e.g. implantation without experimental and numerical investigations.

The experimenter when conducting biomechanical investigations, particularly of human structures, should take into consideration several factors:

- Measurement repeatability – it is often the case that experiments are thought to have been carried out under identical conditions, but the results obtained differ significantly. The measurement repeatability often depends on the precision with which the measuring points are located and on the arrangement of the directions and points of application of loads.
- When investigating tissue structures one may encounter some problems associated with the material properties of an element investigated:
  - constant and repeatable properties of specimens;
  - the effect of temperature and hydration on physical properties of tissues;
  - phenomena dependent on the duration of loading, such as creep.
- Human factors such as preparation of an experimenter (biomechanical engineer, physician) for the investigations and his knowledge of the anatomical and physical properties of the tissue structures investigated.
- Repeatability of measurements, i.e. obtaining similar results under the same conditions settled in other laboratories.

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