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BIOMECHANICAL ASPECTS OF ARTIFICIAL JOINT IMPLANTATION IN A LOWER LIMB

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One of the most important trends in engineering biomechanics is experimental and numerical analysis of the stress and strain state existing in organs subject to a heavy load; e.g, the knee and hip joints. Clinical tests experimental and numerical studies on design of implants replacing damaged organs are also of crucial importance in development of biomechanics. The research is focused on determination of loads, experimental techniques as well as on simplifications assumed in measurements and applied models. The conducted investigations were concerned with estimation of mechanical behaviour of hip and knee implants after arthoplasty. The experimental tests on both the real objects and models were performed. Numerical simulation was made by using the finite element method. The tests have proved that from the biomechanical point of view proper selection of endoprosthesis is of crucial importance for achieving positive long-term results of alloplasty.

Key words: biomechanics, implantation, hip joint, knee joint

1. Introduction

Bearing in mind its motor function, the lower extremity is one of the most important parts of the human body. Basically, a person's physical fitness is conditioned by the ranges of hip joint and knee joint mobility. The hip joint is subject to a heavy load, which increases distally attaining high values in the knee joint. Therefore, the two joints are often mechanically damaged. The treatment of degenerative changes within the hip and knee joints is thus one of the most demanding tasks for orthopaedists. At present, surgical methods of total hip arthroplasty and geometrical correction of limb axis are widely used. These methods, however, are accompanied by a relatively high percentage of postoperative complications. Still, joint alloplasty is very often the only method of retaining biological functions of the lower limb. Especially in older patients, whose skeletal system reveals poor self-regenerative capability. Wide use of joint alloplasty, which has been extended considerably over the last three decades is stimulated by scientific and technological achievements in orthopaedics, surgery, bioengineering and especially in biomaterial technology and biomechanics. The lower limb joint alloplasty has become one of the most important operative procedures in the present century.

The most frequent reasons for alloplasty treatment are:

- Osteoporosis
- Dysplasia of the hip (congenital defect)
- Varus and valgus deformity of the knee joint
- Mechanical injuries
- Degenerative changes
- Excessive joint instability.

At present, numerous research projects on improvement of endoprostheses are being carried out because of a still significant percentage of implant failure. Although it has been a long time since the first alloplasty was made and despite clinical and experimental studies undertaken on improvement of this method of treatment, there are still many unsolved problems The main reasons are:

- Latent and symptomless beginning of the loss of implant/bone bonding
- Unexplained pathomechanism of some clinical symptoms
- Insufficient knowledge of factors leading to an aseptic loosening of endoprosthesis
- Excessive wear of articulating surfaces of the endoprosthesis.

Many years of alloplasty testing have shown a 15% failure rate. Consequently, reoperations were necessary, cf Albrektsson et al. (1990), Będziński (1997) Będziński et al. (1998), Freeman (1994). Observation of cementless alloplasty cases, which has been carried out in the Orthopaedic Clinical Hospital of Wroclaw Medical Academy for the last few years, has shown that in this case the failure rate was much lower, cf Dragan (1992). Rather the stem than the acetabulum, is loosening after total hip alloplasty. In the case of the knee alloplasty that concerns the tibial component.

From the biomechanical point of view the most frequent causes of implant loosening are:

- Wrong planning and bad operative procedure performance
- Non-physiological implant/bone load transmission
- Wrong design of prosthetic components
- Implant/osseous substrate strain discrepancy
- Lack of implant/bone biological compatibility
- Inferior quality of the osseous substrate.

Statistically, after lower limb joint alloplasty a high rate of complications arises due to both clinical and biomechanical factors. Insufficient knowledge of biomechanics of the system (lack of a proper models of bone/implant interfaces, inadequate knowledge of physical phenomena occurring after the implantation as well as of their mechanisms and consequences) results in loss of the implant/bone integrity. Quality requirements for the operative procedure performance and its subsequent effectiveness have been, from a clinical perspective, widely discussed in the literature, cf Będziński (1997), Bernakiewicz et al. (1997), Ewald et al. (1984). The clinical criteria for a successful procedure and endoprosthesis selection are known and applied in practice. From the biomechanical point of view, however, the problems accompanying arthroplasty are still to be solved.

Despite the current availability of various endoprosthesis designs, no criteria for the stem selection for hip arthroplasty have been established. Similarly, there are no criteria for choosing the right method for the tibial component fixation, which would allow for a suitable strain and stress distribution within the bone. The nature of distribution, values of strain and stress and especially the existing discontinuities and concentrations of stress may, to a large extent, cause undesirable results of bone remodelling leading to loosening of endoprosthesis. With improper stress distribution and wrong implant selection the process may lead to the implant loosening. Bone/implant stiffness correlation as well as the implant shape and mechanical properties influence significantly the of bone/implant system functioning. These factors determine the values and form of strain and stress distribution within the bone.

A correct estimation of mechanical properties of the osseous tissue allows one to choose most accurate type of implant in the mean of it survival time. Furthermore, it enables one to foresee in a biomechanical perspective the changes occurring in the bone after the implantation That may be helpful in predicting the *life expectancy* of the stem placed in the bone.

The development of lower limb joint alloplasty aims at finding the solution to both biomechanical and biological problems. In biomechanics, the attention is mainly focused on investigations into the effect of implant structure on the changes occurring within the bone tissue. Thus, in biomechanics, the problems connected with alloplasty result from:

- Lack of biological compatibility of the endoprosthesis materials
- Inferior quality of the osseous substrate
- Insufficient bone tissue ingrowth into implant surfaces.

From the literature, cf Będziński (1997), Będziński and Ścigała (1998), de Jong (1997) one can conclude that there is no comprehensive approach to these problems and that hardly any research has been conducted in the field. It is well known that strain and stress distribution under physiological load is extremely complex and still unexplained. The disturbance of physiological state due to implantation of artificial element inside the bone, and the change of natural load distribution in the joint might strongly effect on the values and distribution of stress and strain in the bone tissue. A complex and still not entirely explained nature of the implant/bone system functioning renders it difficult to choose the right treatment method and to optimise operative techniques. It may also be the reason for alloplasty failures.

Many research programmes focused mainly on understanding of the causes of aseptic loosening of endoprosthesis, cf Carter et al. (1977), Garg (1986). The aseptic loosening is a gradual process leading to disturbance in bone/implant mechanical integrity.

Simultaneously, fibrous tissue forms in the interface between the osseous tissue and the endoprosthesis stem. Its gradual growth in time is the main cause of all complications.

From the clinical point of view, the essential issue consists in specification of the requirements ensuring bone formation. Meeting of these requirements should enable one to lastingly place the implant in the bone. The loss of primary stability leads to micromotions between the implant and bone. From the clinical point of view, instability of the endoprosthesis component manifests as pain and limitation of joint mobility. Consequently, it is often necessary to re-implant the endoprosthesis. Consider now conditions for obtaining satisfactory bone/implant system:

Firstly, in hip arthroplasty fixation of the stem in the bone consists in mechanical filling of the gaps existing between them. Therefore, the size and shape of the stem are of crucial importance. The techniques of preoperative preparation of the femoral canal for the endoprosthesis stem are also essential.

The question of producing suitable equipment to execute the task has not been solved yet. Consequently, the internal postoperative fixation of the implant is far from perfect. In knee arthroplasty it is important to fit adequately the shape of the stem of the tibial component with the bone substrate. The available modular systems of knee joint implantation enable one to select the right length and shape of the stem and also of the fixing accessories (e.g. surgical screws). Analysis of the effect of both the terminal tibial component and the way of its fixation on the state of strain in the osseous tissue is then necessary. The process of endoprosthesis loosening has not been satisfactory explained but it is believed that the life expectancy of endoprostheses depends on the state and rate of joint loading, type of loading as well as on the kind, value and distribution of stress that forms due to the transmission of load from the endoprosthesis onto the bone tissue. Excessive load may result in microcracks and micromotions in the implant/bone region which rapidly propagate with time, Aspenberg et al. (1992), Kendrick et al. (1995)

The other important factor is discontinuity of strain in the implant/bone interface region. Non-physiological nature of load transmission is one of the main reasons affecting the alloplasty failure rate, Andriacchi et al. (1976), Cheal et al. (1985).

It has been shown in clinical practice that elements of endoprosthesis show a tendency to migrate. No evaluation, however, has been made of the effect of value and distribution of strain and stress occurring in the bone under load on the attaining and the subsequent maintaining of endoprosthesis stability after implantation. One of the decisive factors in attaining both primary and secondary stability may be a proper strain and stress distribution at the interface between the implant and bone tissue. It is essential here to maintain the continuity of strain and stress and to prevent their concentrations.

On the grounds of the analysis of clinical cases and the tendencies in stem design development, one can conclude that biomechanical analysis is essential for increasing of probability of long-term success of alloplasty procedure. Especially this kind of procedure allows one to obtain most accurate load distribution in the joint, by correct choice of implant fitted to mechanical properties of bone tissue, Będziński et al. (1985), Będziński (1994), Cheal et al. (1984). Strength quality of the design is a function of both geometrical structure and the material parameters as the Young modulus and Poisson ratio. A successful design, and suitable implant selection, requires determination of changes of strain distribution over both the bone structure and implant, which must include complex loading conditions. Available implants are made of materials of various strength properties. The design features of endoprostheses affect decisively the process of reaching stem stability in the bone.

So far, the criteria for optimisation of endoprosthesis designs have not been established. Moreover, even the factors allowing creation of new criteria or changes of existing one are not defined. One is also lacking in an accurate qualification of the state of loading predominant in the lower extremity after the implantation of the endoprosthesis. The joint replacement would always change the conditions of load transmission in a lower limb and therefore it influences significantly the form of distribution and the state of strain and stress occurring in the bone after implantation. In many professional reports a lot of attention has been focused on both the research into bone mechanical properties, Carter et al. (1977), Goldstein et al. (1983) and understanding as well as mathematical description of the factors governing the processes of bone tissue remodelling, Carter (1986), Ducheyene et al. (1977), Frost (1964). All the models, however, present a striking contrast with in vivo conditions, that is mainly caused by oversimplifying assumptions accepted and by employing the coefficients which have been experimentally obtained in a simplified way. Moreover, the formulated constitutive equations of bone tissue are generally based on models of elastic and viscoelastic materials, which is quite an oversimplification.

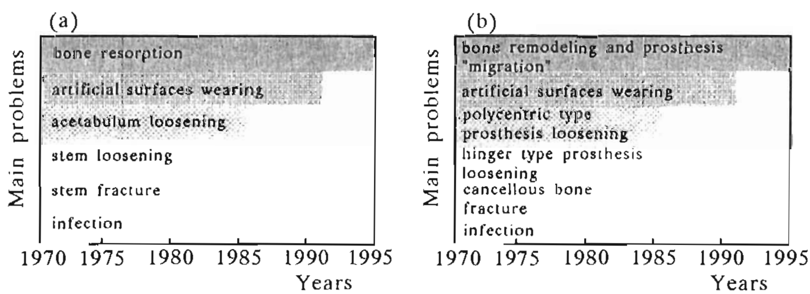


Fig. 1. The order of problem solving relative to hip (a) and knee (b) joint alloplasty in the last years

Summing up, despite a long time past since the first alloplasty and rapid technological progress, arthroplasty is still accompanied by a number of unsolved problems, which become evident in a high implant failure rate revealed by clinical statistics (Fig.1). Though such problems as infections, fracture of stems and hinge-type knee prosthesis loosening have been solved as a result of technological progress, mechanical causes of stem loosening still remain unknown. Also bone remodelling around implant needs further investigation.

One of the factors of procedure effectiveness improvement may be assessment of criteria for the evaluation of structural parameters of commonly used implants. This problem does not seem to have been extensively discussed in the literature. The parameters may enable orthopaedic surgeons to ground the selection of endoprosthesis not only on clinical data but also on equally important biomechanical aspects. There are some discrepancies and ambiguities in the literature that may have been caused by specific properties of the examined objects (individual changes) and a variety of simplifications and boundary conditions used in investigations.

When studying the literature one meets many open questions; e.g.:

- Deeper understanding of bone tissue remodelling around the carrying element of endoprosthesis
- Stress shielding phenomena
- Test methodology used in the evaluation of endoprosthesis designs.

Other important issue consists in the fact that the proper assessment of the effect of stem design on the bone/stem system functioning requires construction of suitable models which would allow for extreme states of loading.

Many experimental and numerical methods of solid mechanics have been applied to analysis of the stress and strain state in the bone/implant system. The study of recent literature shows that the strain gauge method is mainly used in experimental investigations into the bone/implant system, Friedebold and Wolff (1987) (other frequently used methods: photoelasticity, Hank et al. (1988), holographic interferometry and speckle photography, Garg (1986), Hanser (1979)). A mechanical description of bone material properties and its geometry is very complex. Therefore, a method employing in vivo measurement seems to be most advantageous. The drawback of the strain gauge method consists in its point-by-point measuring procedure, which renders it difficult to select proper measuring points and to predict measurement results in locations surrounding these points.

Summing up the present analysis of research findings we conclude that many experimental research programmes have focused mainly on:

- Analysis of the strain state in artificial joints and the adjoining osseous tissue, cf Albrektsson et al. (1990), Rohlmann et al. (1983)
- Analysis of micromotions of the implant against the human bone, Ebramzadhed et al. (1988), Philips et al. (1990), Ryd (1986), Ryd et al. (1988), Tissakht and Eskandri (1995)
- Optimisation of implant design features, Beaupre et al. (1986), Delp et al. (1994), Murase et al. (1982), Van As et al. (1995)

- Analysis of bone/endoprosthesis system functioning under variable loading conditions, Hanser (1979), de Jong (1997).

Despite a variety of investigations conducted the experimental results differ substantially when compared with the in vivo ones. There is still no agreement about essential issues, such as:

- Research methodology (repeatability of measurements)
- Selecting appropriate measurement techniques
- Boundary conditions (material and geometrical properties of samples; states of loading).

Therefore, it is difficult to compare the results published so far. Moreover, investigations seem to be fragmentary and there is no comparative study on a comprehensive biomechanical evaluation of currently available hip endoprostheses.

2. Materials and methods

In the case of hip joint, various types of stems of hip endoprosthesis used in clinical practice were the objects of present research. The effects of stem geometry, state of loading and bone mechanical properties on the nature of bone/stem system functioning were thoroughly investigated. Two types of non-cemented stems of hip endoprosthesis had been selected for examination. Though their material properties were similar, their structural properties differed substantially.

Table 1. Characteristics of the selected stems of hip endoprosthesis

Type of stem	Size	Material	Structure description
KERAMED GSS-CL	3	Ti6Al4V	non-cemented, straight, collarless, long, one-third of porous coating, rounded in cross-section
PM	13	Ti6Al4V	non-cemented, straight, with a collar, long, one-third of porous coating, rounded in cross-section

The experimental examination aimed at comparative analysis of displacements within model hip bones with various types of stems implanted (Fig.2). The material properties and geometrical features of the models were constant

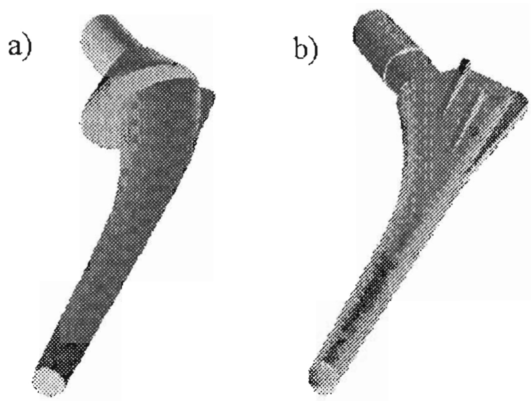


Fig. 2. Analysed system (a) PM stem, (b) KERAMED stem

and known. The investigations made it possible to determine the effect of bone/implant rigidity on the bone displacement. The analysis of displacement distribution in model bones with various types of stems enabled one to evaluate design features of stems and the nature of stem/bone system functioning. This comparative analysis was carried out for physical models of artificial hip bones.

The analysis of hip and tibial bones displacement under load in both single and double leg stances in the position of full knee extension is an example of the knee joint analysis using the holographic interferometry (Fig.3). The physical model under consideration of the anatomically and physiologically intact knee joint, was made from the real human bone resected from cadaver and prepared for measurement.

The aim of the analysis was to qualify the displacement in the joint under physiological load and to define the tendency of the loaded joint to deform. On the basis of displacement recordings of the femur borne on tibial condyles it was possible to roughly estimate joint stability dependent only on the shape of articular surfaces.

That was only one of the stages of comparative investigations into the knee joint, which aimed at defining postoperative results of axis correction.

In the case of the hip joint, the aim of simulations employing a finite element method was an analysis of the state of strain within the femur implanted with a stem. In the case of the knee joint, the investigations included an analysis of the state of strain and stress in both the femur and the tibia implanted

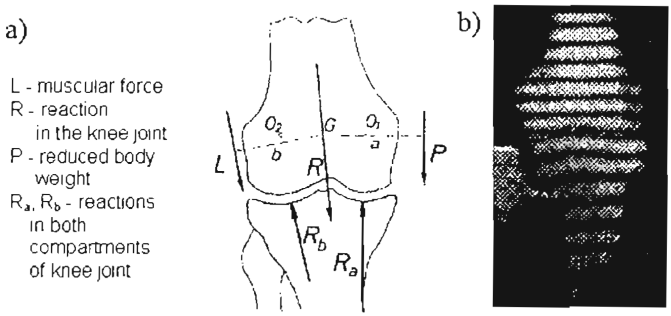


Fig. 3. Applied loading (a) and a sample interferogram (b)

with components of the condylar prosthesis. The investigations made way for a qualitative and quantitative evaluation of the functioning of the implanted osseous tissue under a complex loading state. Moreover, they helped to explain in a biological perspective the causes of the formation of systemic lesions and the reasons for alloplasty failure. They also enabled one to analyse the effect of implant design features on the nature and state of strain in the hip bone. The adopted material properties of bone tissue corresponded with those of artificial bone. While setting model bones with stems of hip endoprosthesis actual geometrical relations of physical models were retained (numerical models reproduced geometrically physical models, which had been clinically made).

The following terms were accurately reproduced:

- Method of resecting the femoral head
- Way of preparing the bone canal
- Positioning of the stem in the bone canal (antetorsional angle, collar support, the head of stem retaining the distance of the actual head of bone).

With the knee joint, the following terms were reproduced:

- Method of resecting of the tibial plateaux
- Proper positioning of the anatomical axis of the femur in relation to the tibia
- Method of resecting surfaces of femoral condyles.

A stiff stem/bone bonding was assumed (especially, in upper regions of the femur in the case of hip joint and for all implant/bone-tissue interfaces in the case of knee joint) as well as proper conditions of secondary stability. In the case of collarless stems of hip endoprosthesis the layer binding the bone with the stem in lower regions of the stem was also modelled (material coefficients of the layer were assumed to be one order of magnitude lower than those of cancellous tissue), which had to be taken into consideration because of micromotions of the stem end in the bone canal.

A TETRA-kind, volumetric, tetrahedral, 10-node element was the base for discretisation of the model. Numerical models of the stem/bone system for KERAMED and PM types of stems of hip endoprosthesis were generated. They were also generated for the SEARCH type of knee endoprosthesis. The models of the femur and femur with the stems implanted consisted of 75 000 elements, 350 000 degrees of freedom. Model of knee joint with the Search prosthesis implanted consisted of 70 000 elements, 280 000 degrees of freedom.

3. Experimental results

3.1. Hip joint

The stem length as well the stem type (collar or collarless) and the stem bending stiffness, i.e., material properties and geometry of the cross-section were taken into account in present investigations.

The impact of the above factors on the nature and state of bone displacement under loading conditions was analysed. Artificial bones with implants were tested (Fig.4a). Selection of the stem size was made on the basis of clinical criteria. The scheme of optical set-up for holographic interferograms recording and the load measuring set-up are shown in Fig.4c and Fig.4d. The state of bone/stem deformation was defined on the basis of interference fringes pattern (Fig.4). The loading system reproduced in a simplified way the phase of walking when the heel meets the ground. From the activity point of view, the most importanat is the walking capability, but the results of load acting in a 16-phase walk and during a static single-leg stance are similar. The deformation of bone in both cases is similar but the values of observed displacements are different. The system was examined under quasi-static conditions. Hip bending and torsion are then the dominant states of loading. The bending is caused by the resultant force acting on the femoral head while the torsion results from interaction of the following muscles: Adductor longus, Adductor

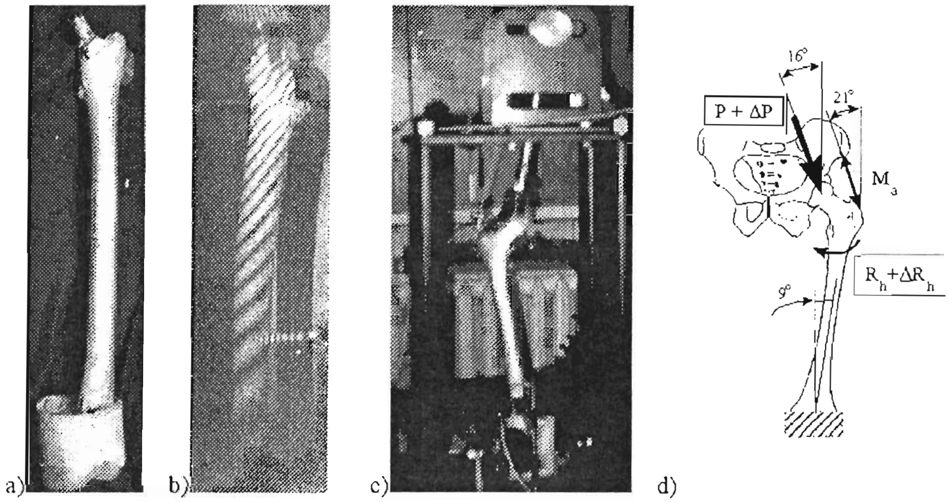


Fig. 4. Bone model with stem implanted (a), sample interferogram (b), interferogram recording station (c), diagram of the loading system (d)

magnus, Gluteus maximus and Semimembranosus. Both the resultant force acting on the femoral head, the muscle force stabilising the pelvis and the force appearing in the muscles attached in the region of the lesser trochanter, responsible for the hip rotation, were modelled. The initial values and the increment of the resultant force acting towards the femoral head equalled $P + \Delta P = 400\text{N} + 5\text{N}$ and the increment of force of hip rotating muscles equalled $R_h + \Delta R_h = 80\text{N} + 2.5\text{N}$. This model allowed for recording of the state of bone strain under simplified conditions of walking.

The experimental investigations made it possible to evaluate stem designs and their effect on the stem/bone system functioning. Since the bending load is predominant (due to physiological conditions), bending stiffness is an important parameter in evaluation of the following stem design features: material properties, type of transverse cross-section, cross-sectional longitudinal changes and stem length. The analysis of the state of stem/bone deformation enabled one to evaluate the effect of these features on the nature of stem/bone system functioning. The KERAMED stem co-operating with the bone brings about a considerable change of displacement distribution (Fig.5). Its contraflexure point occurs in the stem end region. Moreover, it causes a large displacement gradient in the proximal stem region.

This indicates a considerable disturbance of the physiological stem/bone system functioning, leading to formation of the strain shielding zones in the

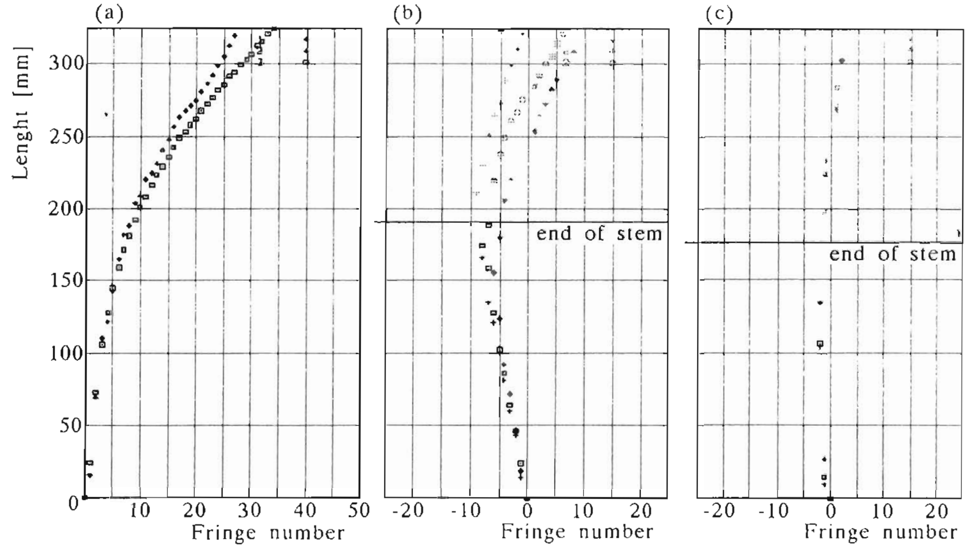
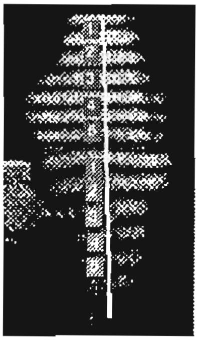


Fig. 5. Distribution of the displacement as function of interferometric fringe number for (a) intact bone, (b) bone with implanted the KERAMED stem, (c) bone with implanted the PM stem (1,2,3 – tests number)

bone. This effect will also result in considerable differences of the remodelling process rates in the proximal region. In addition, it may also lead to an abnormality of the remodelling process and consequently to undesirable decrease in bone strength or lack of regular stem/bone binding). The displacement distribution in the PM stem implanted in the bone differs substantially from the results observed for the intact bone. The impact of the collar is evident. When it is present, the contraflexure point occurs in the lesser trochanter region where significant changes of displacement occur. This effect may also result in strain and stress concentrations in the very region and in increasing stem micromotions.

3.2. Knee joint

The analysis of obtained interferograms was carried out for the femoral and tibial elements lying along a vertical line passing through the geometrical centre of the knee joint. The nature of interference fringes implies lack of the displacement component that would indicate shank or hip torsion. The position of the bones is similar to the first phase of joint flexion. The state of displacement of femur bone borne on the tibial condyles, indicates very stable position of knee joint. This observation allows us to confirm the thesis, that in position of full leg extension the shape of femoral and tibial articular surfaces plays most important role in knee stabilty (Fig.6).



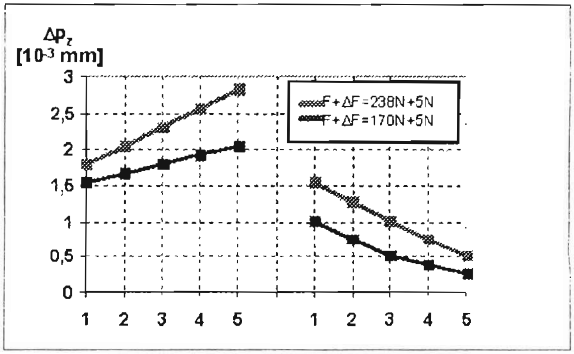


Fig. 6. Diagram of the femoral and tibial bones displacement in the sagittal plane in the phase of full extension (intact joint model)

The investigations made it possible to compare the states of displacement in knee joint bones under varying loading and also after an operative correction of limb axis. Test methodology elaborated for biomechanical objects is, in this case, extremely useful also for other surgical procedures performed in the knee joint region.

4. Results of numerical simulation

A static analysis of the state of strain and stress was carried out. The effect of implant design on the state of strain and stress in the bone was evaluated. An analysis of the rate of effort of the osseous structure made it possible to evaluate hip joint stem designs and tibial components of the knee joint with regard to strength. It also helped to determine the impact of strength factors on stem loosening in the femoral canal and migration of the tibial component of knee joint endoprosthesis. The loading conditions in the models of femur and femur with the stems implanted, respectively, were assumed after Bernakiewicz (1998) for a single leg stance. Besides the resultant force of 2.47 BW (body weight), also the forces generated by three other muscles and tendon acting in this phase of gait were simulated; i.e., Gluteus medius – 0.535 BW, Gluteus minimus – 0.2 BW, Iliopsoas – 0.865 BW and Tractus iliotibialis 0.08 BW. The body weight for the considered model of femur was equal to 567 N. In the lower part of femur (on the condyles) the model was fully constrained.

Only the influence of stem shape, geometrical and mechanical properties on the observed parameters were investigated. Because of numerical simulation simplifications only this kind of comparative analysis was possible. Thus, the Huber-Mises form of the strain energy was applied. The KERAMED stem generates considerably lower values of strain and stress, when compared with the values recorded for the intact bone, changing strongly the strain and stress distribution. As a results only bending occurs in the lateral plane. The strain distribution shows concentrations in the subcollar region. However, both stems generate substantially different distributions of stress observed in the medial part of femur when compared with the intact femur (Fig.7).

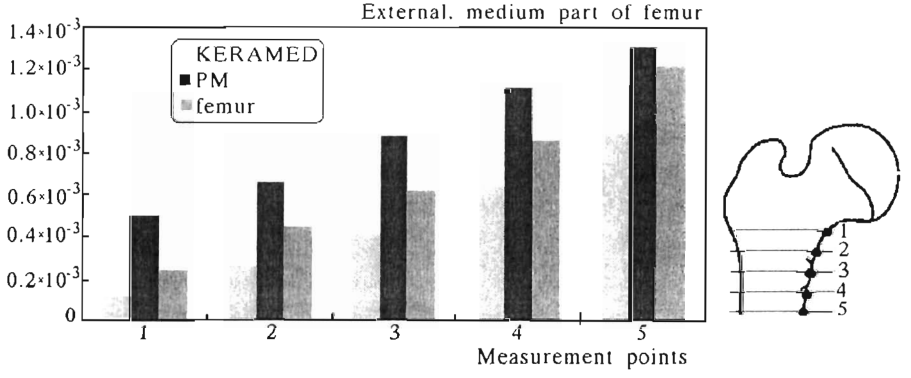


Fig. 7. Strain values in the analysed cross-sections reduced according to the Huber-von Mises hypothesis

Moreover, there is a non-uniform stress and strain distribution around the stem in a transverse cross-section. Analysis of the values of strain occurring in the bone in the bone/stem interface region, indicates that both stem designs affect a strongly non-uniform and discontinuous strain distribution (Fig.8).

The PM stem design yields lower values of bone strain wen compared with those obtained for the intact bone. Besides, the PM stem alters decisively the stress and strain distribution causing that the bending in the lateral plane of bone becomes a predominant factor. The collar leads to a non-uniform strain distribution and high values of strain arising in the bone subcollar region. The strain distribution over the stem/bone interface is characterised by irregularities and concentrations especially in the mid-length stem region. Moreover, there are discontinuities in the strain distribution around the stem in trans-

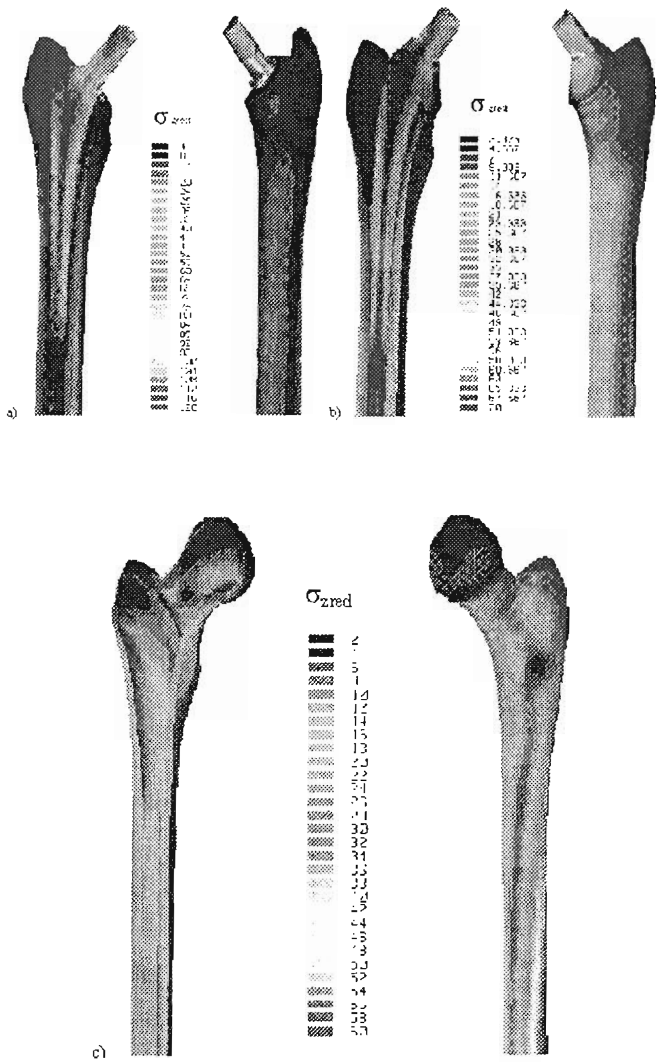


Fig. 8. Distribution of the stress reduced according to the Huber-von Mises hypothesis (in MPa) for (a) bone/KERAMED stem system, (b) bone/PM stem, (c) the femur

verse cross-sections. The form of strain distribution indicates an abnormal process of implant/bone load transmission. When analysing the value of reduced strain occurring in the bone in the bone/stem interface region, one can notice, that the PM stem leads to a strongly non-uniform and discontinuous principal strain distribution. The maximal values of strain occur in the bone mid-length.

The loading conditions of knee joint, used in numerical simulation, were assumed after Maquett model (Fig.3). The resultant force $R = 1440\,\mathrm{N}$ was divided into the two components acting on condyles $R_a = 980\,\mathrm{N}$ and $R_b = 470\,\mathrm{N}$. This model simulates a single-leg stance.

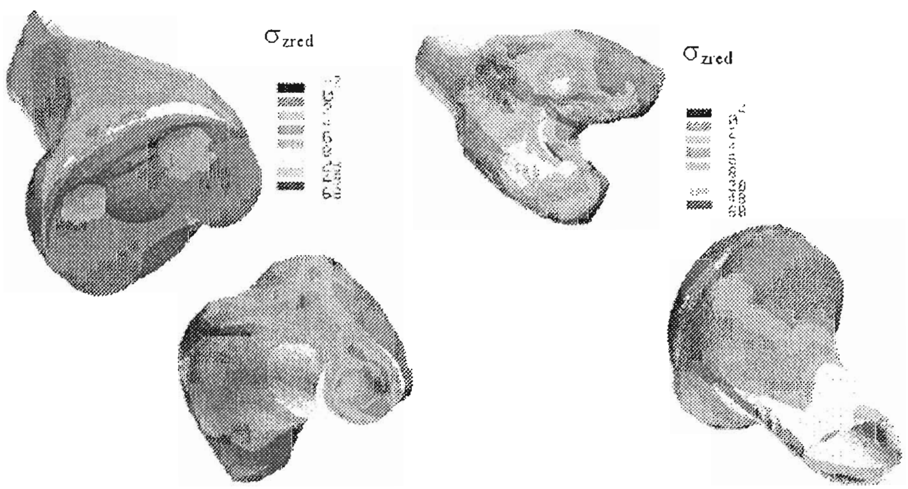


Fig. 9. Distribution of Huber-von Mises stress (in MPa) subjected to axial force in the position of full extension

In clinical practice, the importance of the method of fixation of the tibial component of knee endoprosthesis has been often emphasised, Ryd et al. (1990), (1995). Modular solutions, which enable one to adapt the method of fixation of endoprosthesis to the state of bone tissue in tibial epiphysis during the procedure, are used in the case of endoprosthesis reconstruction in a model knee joint. The method consists in using replaceable stems of clearly different designs, Andriacchi et al. (1976).

The changes, which occurred within the tissue surrounding the stem of the tibial component and caused by the overloading have been frequently observed in clinical practice, Carter (1986).

The distribution of the reduced stress in all models is shown in the Fig.9. High pressure at the stem end causes a permanent lesion of a fragment of

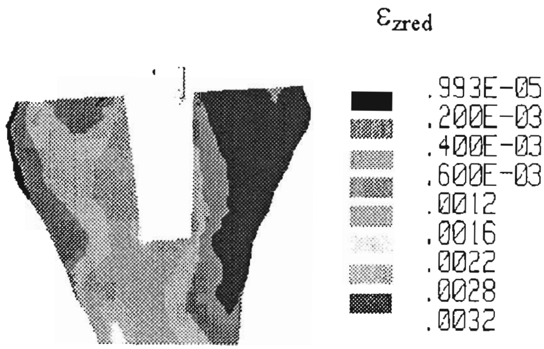


Fig. 10. Distribution of strain (in $\mu\varepsilon$) in the frontal plane

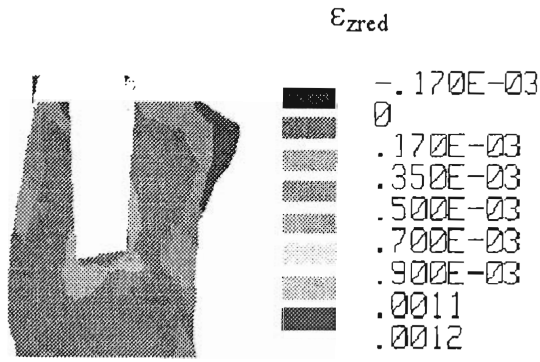


Fig. 11. Distribution of strain (in $\mu\varepsilon$) in the sagittal plane

cancellous tissue and progressive loosening. In this case strong strain concentrations have been observed in the posterior (Fig.10) and lateral (Fig.11) parts of the tibia. This may indicate that despite a proper implantation of both endoprosthesis components, the limb varus deformation may develop while overloaded. It affects also the strain distribution in the tibial part of endoprosthesis (Fig.12).

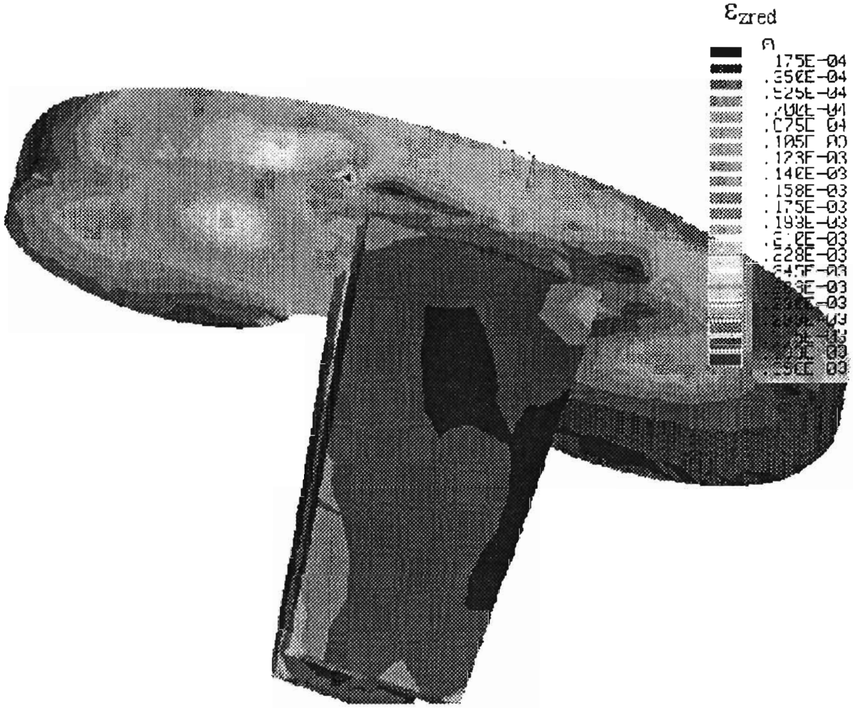


Fig. 12. Distribution of Huber-von Mises strain (in $\mu\varepsilon$) the tibial component of endoprosthesis

5. Discussion

5.1. Hip joint

Generally, from the clinical point of view, neither toxic nor allergic reactions irritating the bone tissue should be produced by a perfect implant, i.e the implant should be biologically compatible with the human body. For a proper resistance to loading, hip joint implants require a firm biological fixation, which may mainly result from bone tissue ingrowth into the implant. A preciptate full loading or incorrect fitting of endoprosthesis stem to the femur canal might by reason for slight micromotions of the implant in the bone. Next, it will result in cancellous bone growth. This may consequently lead to implant loosening.

On the other hand, from the biomechanical point of view, the stem design is crucial for proper functioning of the implant. Such a design ensures desirable implant/bone load transmission. Consequently, this influences a desirable distribution of strain and stress in the bone. These factors determine the bone remodelling process around the stem, which in turn facilitates a long-term success of the procedure.

After a series of investigations the most important stem design features have been evaluated in the bone/stem system functioning perspective:

- Stem length. The stress and strain distribution is closest to that observed in the intact bone when short stems are applied, Bernakiewicz (1998).
- It has been found that the collar plays a crucial role in achieving secondary stability of the stem. It produces, however, strain and stress concentrations in the subcollar region which, change decisively the implant/bone load transmission and contribute to an abnormality of the process of bone remodelling. A disadvantageous effect of the collar on the nature of stem/bone system functuining has been found in both the experimental investigations and numerical simulation. The investigations also show the occurrence of higher stresses in the bone in the proximal part of collarless stems when compared with those observed in stems with collars.
- The bending stiffness of the stems plays an important role in mechanical Cupertino of stem and femur. Cross-sections of the objects without corners reveal a high regularity of strain and stress distribution in the bone. There is a lack, in literature, of the reports on the optimisation of endoprosthesis from the point of view of stem/bone stiffness relationship. It is unequivocally stated that this relationship is of crucial importance for maintenance of the normal bone/stem system functioning under physiological loading. The values of strains and stresses in the bone decrease considerably with the increase of stem elastic modulus, Cheal et al. (1984), Huiskes et al. (1992). Higher values of stem elastic moduli reduce strains in the proximal metaphysis of the hip bone. Materials with a low elastic modulus (e.g. titanium alloys) are much more suitable, from the mechanical point of view, for hip endoprosthesis stems than materials with a high Young modulus. None of the materials known so far meets simultaneously all the criteria.

5.2. Knee joint

Capabilities of numerical analysis carried out with the aid of modern methods of solid mechanics facilitate a multifaceted analysis of biological and mechanical processes occurring in complex biomechanical systems. The problems that arise while making such an analysis are mainly associated with selecting joint loading models and defining the conditions of Cupertino of particular components of the model. Moreover, it should be emphasised that in order to evaluate properly interaction between the applied endoprosthesis and human tissue, interrelations between numerical models, experimental investigations and clinical observations should be established, allowing for verification of numerical models.

The further research will therefore concentrate on experimental verification of the results published in the present report.

6. Conclusions

Rapid technological progress has enabled analysis of many cases clinically qualified for hip or knee joint alloplasty. High costs of currently produced endoprostheses, resulting mainly from manufacturing technology, limit wider use of a custom-design. Still, the criteria for implant selection established with regard to effort and bone/implant interaction make it possible to choose from the available designs the one suitable for each individual case. These criteria should supplement a clinical evaluation and selection of the endoprosthesis, which can satisfy the biomechanical requirements of the bone/implant system. The clinical evaluation of endoprosthesis designs, which would adopt the established criteria, should, in each individual case, be relatively easy. It requires only a short series of simple analyses and simulations. The CT examination may, for example, result in a geometrical model of the analysed hip or knee bones. Measuring bone density, one may, on the basis of empirical relation given in the literature, determine the bone material properties needed for the FEM simulation. Employing (after individual scaling of weight) the established loading models, it is possible to perform a finite element simulation in order to evaluate the analysed endoprosthesis designs on the basis of distribution and values of strains and stresses.

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Biomechaniczne aspekty implantacji sztucznych stawów kończyny dolnej

Streszczenie

Jednym z najważniejszych kierunków badań w dziedzinie biomechaniki inżynierskiej jest doświadczalna i numeryczna analiza stanu odkształceń i naprężeń w organach ludzkich poddanych znacznym obciążeniom, jak chociażby staw biodrowy i kolanowy. Badania kliniczne, doświadczalne i numeryczne poświęcone konstrukcji elementów zastępujących uszkodzone elementy ciała ludzkiego stanowią jeden z najważniejszych kierunków rozwoju biomechaniki. Dyskusje na tym tle skoncentrowane są na problemach determinacji występującego stanu obciążenia, stosowanych technik pomiarowych oraz uproszczeń warunków pomiaru i przyjmowanych modeli. Przeprowadzone badania poświęcone zostały ocenie mechanicznej współpracysztucznych elementów stawu biodrowego i kolanowego w warunkach implantacji. Badania przeprowadzono zarówno technikami doświadczalnymi na obiektach rzeczywistych i w warunkach modelowych, jak i metodą symulacji numerycznej, metodą elementów skończonych. Badania udowodniły duże znaczenie prawidłowej selekcji endoprotez z punktu *widzenia biomechaniki układu na długoterminowe powodzenie alloplastyk.*

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