Acta of Bioengineering and Biomechanics
Vol. 3, No. 2, 2001

Stress distribution in varus knee after operative correction of its mechanical axis

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An analysis of the results of 121 minus-valgizing osteotomies in genu varum performed in the years 1985–1998 allowed the authors to conclude that the recommended by most researchers hypercorrective valgus positioning of the knee's mechanical axis after an osteotomy resulted in increased postoperative valgity in 12 cases. This complication nullified the intended effect of the operation and required another corrective procedure. Clinical observations showed that the probable causes of the complications could be different, e.g. a significant decrease of bone density in the joint's exterior section, taking over the body-weight load, and the patient's considerable overweight. Whereas the presumptive cause was a limited capability of remodelling of the overloaded exterior section of the joint. In order to determine the magnitude and distribution of static forces in the knee's articular ends, a series of measurements were made using spatial photoelastic models as exact geometrical copies of specimens from autopsy. The measurements have shown that in the case of the hypercorrective position of the joint's axis, an extremely heavy concentration of forces occurs on the relatively small bearing surface of the outer condyle of the tibia. This creates adverse mechanical conditions and makes it impossible to obtain the intended correction angle.

Key words: the joint's mechanical axis, varus deformity, valgity, hypercorrection, osteotomy, remodelling, photoelasticity

1. Introduction

Dysfunctions of the motor system, which appear and intensify as the body grows old, have become an important and serious issue, particularly in highly advanced societies. The high level of health awareness, much better medical care and prophylaxis have considerably extended an average life span. On the other hand, industrialization, the development of transport and the beating of records in sports have become factors which in certain conditions may greatly intensify the development of the most common diseases referred to generally as the degenerative joint disease. In the human population, degenerative changes usually occur in the spine in both its lumbar and cervical sections, and less frequently in its thoracic segment. The second and the commonest locus of degenerative changes is the knee joint and the per cent of knees affected by the degenerative process increases with age. If degeneration of a joint is accompanied by the deformation of its mechanical axis, a varus deformation occurs more frequently than a valgus one.

The knee joint degenerates rapidly if degenerative changes are accompanied by the instability and the disturbance of mechanical axis. This leads to the asymmetric distribution of loads on the bearing surface of the tibial condyles (tibial plateaux). At the beginning, bone and ligament remodelling preserves the bone–ligament stability of the joint supported addidtionally by the muscular system. When the remodelling capacity becomes exhausted, the degree of axis deformation and the joint instability increase rapidly and the muscular apparatus is unable to counteract it effectively.

One method of treatment consists in a surgical correction of the joint's mechanical axis, which results in the improvement of the passive, and indirectly active, muscular stability.

In the case of unstable genu varum, the most suitable treatment seems to be a minus-valgizing osteotomy according to Coventry.

At the Orthopaedic Department of the Health Care Institution's Regional Hospital in Wrocław this kind of osteotomies have been performed since 1985. Corrective operations on genu varum with a considerably advanced degenerative process were performed using geometric or "plus" osteotomies, but their long-term results were unsatisfactory. In the years 1985–1998, we performed 121 corrective osteotomies according to Coventry using the operative technique as precisely as its author [3]. Then analyzing the particular cases and the long-term results and keeping track of the literature on the subject we introduced certain modifications into the method [1], [2]. The examinations of the patients and the analysis of the results obtained for a group of patients with the most pronounced deformation did not remove the doubts which had arisen. Why in one case encouraging result was achieved and in another very similar case of the operation carried out according to the same procedure a mediocre or unsatisfactory result was obtained. The available literature did not provide a convincing explanation of our observations. Only a few of many researchers claimed that a surgical correction through an osteotomy was possible and a good result could be achieved even for deformation exceeding 40° [3]–[8] and those reports referred to the period prior to a wider use of knee-joint arthroplasty. Nowadays a varus deformity of the knee's axis can be corrected by an osteotomy if the degenerative process is limited to the knee's medial section, or at the most to the medial and anterior sections, if the varus deformity does not exceed 10–15° and no instability or slight instability occurs [9]–[12].

Surgical correction of a large varus deformity of the joint's axis becomes a serious problem when for various reasons arthroplasty cannot be performed.

The critical moment in the dynamics of the disease process is the exhaustion of the limb's adaptive and compensative capabilities. A key factor here is the remodelling of the bone and the ligaments in the disease-altered and overloaded medial section of the knee [13]–[16]. At this stage of the disease the degenerative process accelerates. The condyle defect becomes more pronounced (tibial plateaux) and the varus deformity and instability increase. The overloaded condyles of the medial section undergo subcartilaginous sclerosis, while the lateral condyles, being unloaded, undergo decalcification. As a result, their mechanical resistance to deformation decreases.

A vicious circle sets in. It can be broken only by restoring the joint's correct mechanical axis through a corrective osteotomy.

2. Material and methods

An analysis of the results of 121 minus-valgizing osteotomies on genu varum performed in the years 1985–1998 revealed that the hypercorrective valgus positioning of the knee's mechanical axis recommended by the majority of the researchers [17]–[20] led to the postoperative increase in valgity in 12 cases. Such a complication cancels the aim of the operation out and it requires another surgical correction [21], [22].

In clinical examinations of the above 12 cases, the radiogram obtaineds were assessed from the point of view of the condition of the subcartilaginous layer and the trabecular structure in the epiphysis of the distal thigh bone and in the epiphysis of the proximal tibia. In addition, densimetric tests were carried out for 6 randomly selected cases. The tests showed a 31–43% (average 37.4%) reduction in bone mass in comparison to bone mass of young people and a 19–40% reduction (average 16.2%) in comparison to bone mass of the middle-age people. Moreover, it was determined that the average (for 12 joints) postosteotomy thigh-tibia angle was 10.2° and the outward displacement of the lower limb's mechanical axis was 20.4 mm. These quantities at the time of the hypervalgity assessment were 22.1° and 46.9 mm, respectively.

The clinical examinations and the assessment of the results showed that the complications were probably caused by a considerable reduction of bone density in the joint's exterior section taking over the body-weight loads, the patient's overweight and axial loading being too early. The limited capabilities to remodel the knee positioned in excessive valgity and a concentration of forces exceeding the mechanical strength of the tissue could also be considered as the causes of problems.

In the process of remodelling, the density of the bone changes as it is remineralized or demineralized. The dynamics of remodelling depends mainly on the organism's capabilities and the kind and direction of the pressure forces. This is a long process and it needs time.

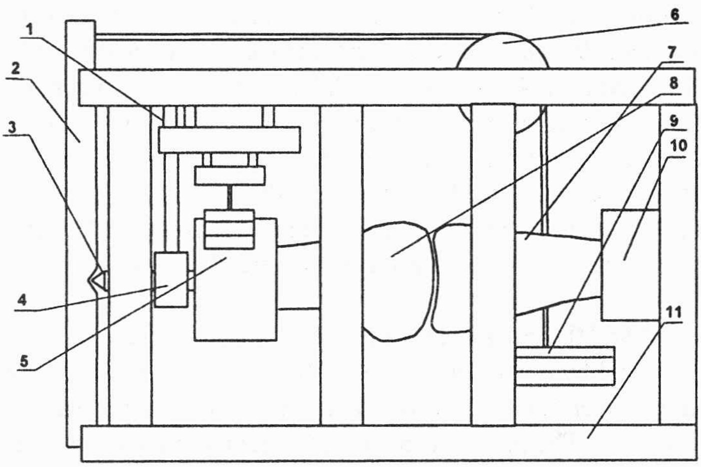
Studies have shown that the skilful exploitation of remodelling-generating mechanisms such as movement and controlled, suitably dosed loading in the period after an osteotomy of the knee joint has an influence on the results obtained [23]–[28]. It is vitally important to combine functional treatment with pharmacological treatment aiding the remineralization of the bone. The purpose of the osteotomy is to restore the joint's optimum mechanical axis and the uniform distribution of pressures on the joint's surfaces [29]–[31].

To determine the distribution and magnitude of the static forces acting on the knee's articular ends, a series of measurements on spatial photoelastic models were made [32], [33].

The models of the bones were based on the actual bones used in the previous stages of the experiment to investigate displacements. The tibial bone, after it had been cut in two and the fragments had been joined, became a protomodel for the construction of a photoelastic model. In a silicone rubber mould prepared, the bone's photoelastic model was cast. A photoelastic model of the thigh bone was prepared in a similar way.

The models of the bones were set in extension and in a valgus position of 10° which was close to the average valgity for the 12 knees investigated. They were subjected to an average model force of 238 N in the limb's mechanical axis (figure 1).

Since it was necessary to "freeze" thermally the stresses in a horizontal position, the loading stand together with the model of the joint were placed in a special cuvette filled with oil.



1 – system loading model specimen,
2 – lever,
3 – pusher,
4 – guide element,
5 – mount,
6 – pulley,
7 – thigh bone model,
8 – tibial bone model,
9 – load,
10 – mount,
11 – frame

Fig. 1. Loading setup for investigations by photoelastic, stress-freezing technique

The hydrostatic lift cancelled out the unphysiologically acting weight of the particular joint-model elements. In addition, immersion in a liquid ensured a uniform heating and cooling of the model during the "freezing" of stresses. The changes of temperature during the freezing of stresses are shown in figure 2. Photoelastic technique enables stress analysis of plane models only.

3.5 mm thick plane specimens were cut out of the three-dimensional thigh-bone models parallel to their face. A scheme of cutting out of specimens is shown in figure 3. Then stress distributions in two-dimensional states of stress were analyzed in a transmission polariscope system.

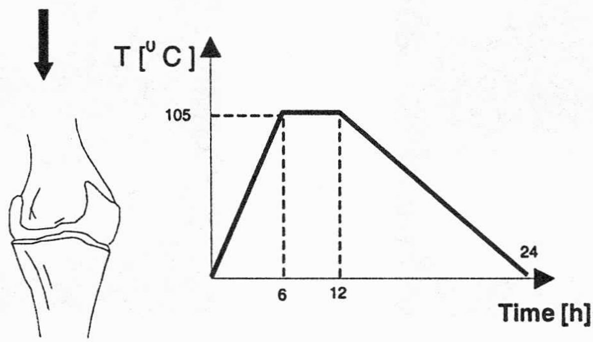


Fig. 2. Changes of temperature during "freezing" of stresses

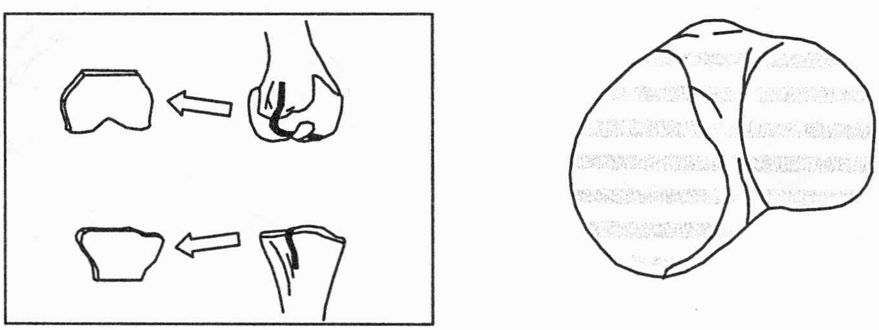


Fig. 3. Scheme the specimen cutting out of thigh-bone and tibial-bone models

3. Results

The examination of the specimens showed that the joint's anterior and posterior parts bear the loads to a slight degree only.

A considerable change in the way of carrying the loads is observed in the central part of the joint. Both the lateral section and the medial section of the joint collaborate in the bearing of loads. One should note, however, that positioning of the model bones at an angle created after a hypercorrective valgizing osteotomy leads to overloading of the lateral section.

A shift of the loading zone results in greater concentrations of stresses produced by the heavier loads that are carried in the medial part of the lateral section (figures 4, 5, 6, 7, 8).

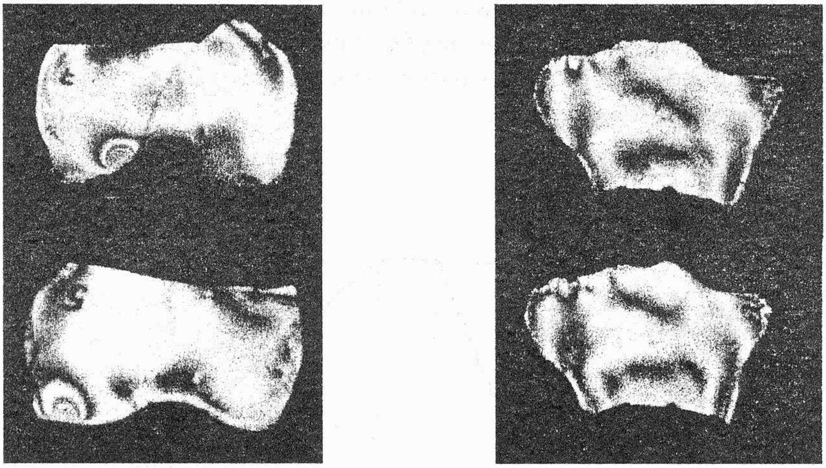


Fig. 4. Images of whole and half isochromatics in condyles of thigh bone after hypercorrective valgus positioning. Visible stress concentration in lateral condyle

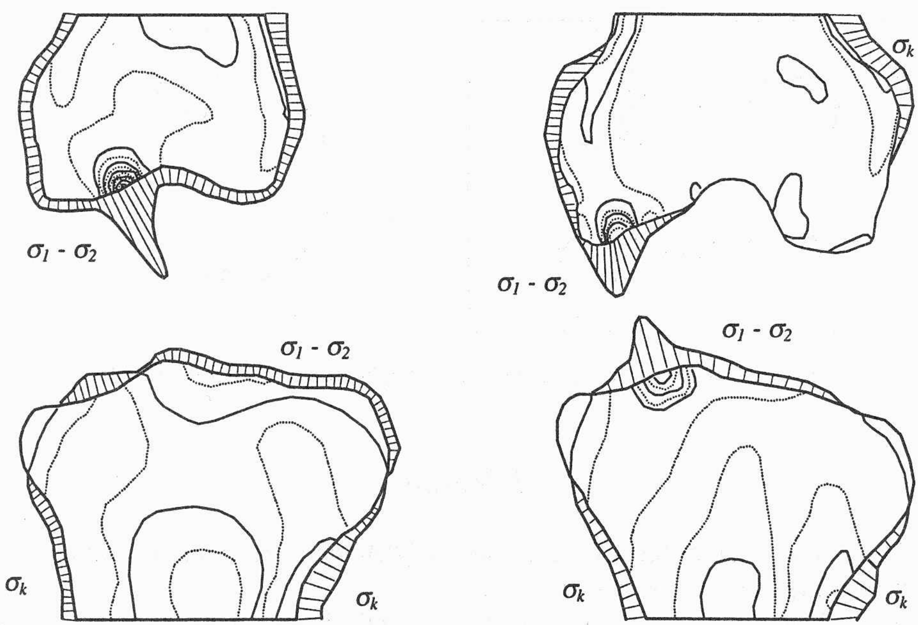


Fig. 5. Distributions of contour stress σ_k and principal stress difference $\sigma_1 - \sigma_2$ in condyles shown in fig. 4

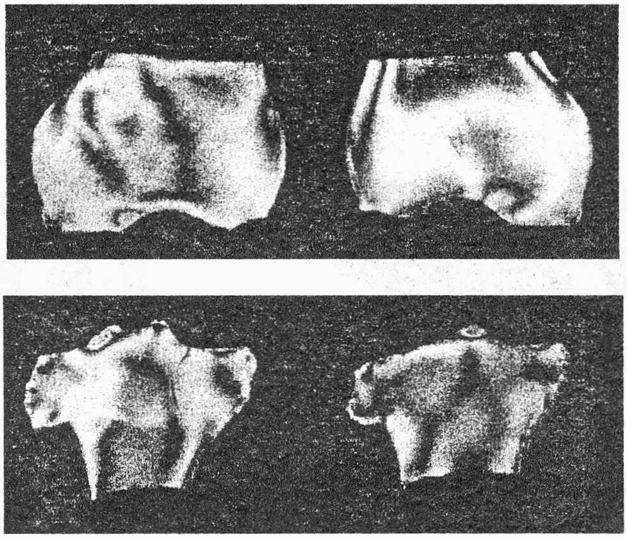


Fig. 6. Images of whole and half isochromatics in condyles of tibia.
Visible stress concentration in lateral condyle

If in the lateral section the bone tissue of considerably reduced density is subjected to high pressures, it will not be able to bear an excessive load and as a result, the deformation of the condyles' bearing surfaces will begin. A subcartilaginous layer

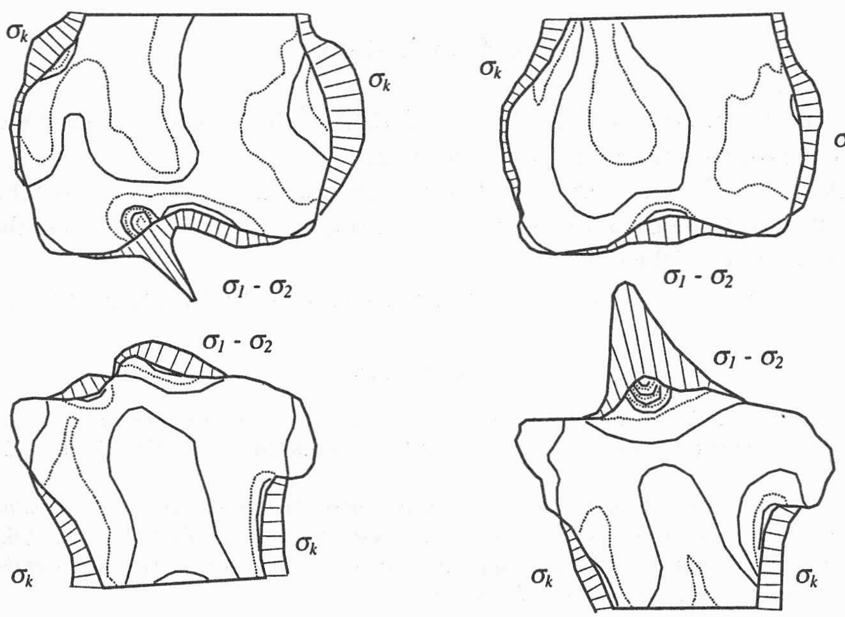


Fig. 7. Distributions of contour stress σ_k and principal stress difference $\sigma_1 - \sigma_2$ in condyles shown in fig. 6

of the bone will start caving in. The lateral condyle of the thigh bone, sinking gradually into the condyle of the tibia, will change the thigh–tibia angle. An undesirable excessive valgity will appear.

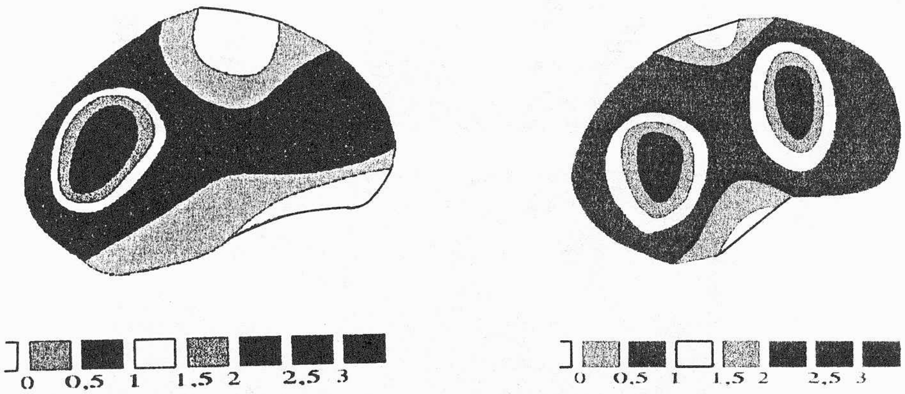


Fig. 8. σ_1–σ_2 distribution on articular surfaces of tibia in hypercorrective valgus position

A comprehensive diagram of the principal stress difference expressed by the orders of isochromatics shows that the loading of the lateral section in this position is much heavier than that of the medial section (figure 8).

4. Conclusions

1. Changes in bone density and remodelling of the knee's articular ends after a valgizing osteotomy are long-term processes.

2. Assessing the necessary correction a surgeon should take into account the density of the bone, the capabilities of the organism, the patient's weight and the mechanical strength of the tibial plateaux.

3. A future loading of the joint being operated should be determined individually.

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