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THE STIFFNESS CHARACTERISTICS OF A HEALTHY OR DAMAGED BY ASEPTIC NECROSIS FEMORAL HEAD

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The goal of the paper is to investigate the stiffness characteristics of bone tissue of healthy femoral head as well as its degradation caused by aseptic necrosis.

Key words: aseptic necrosis, femoral head, stiffness, indentor test

1. Introduction

An important problem in orthopedics is a therapy of aseptic necrosis of femoral head (ANFH). However, despite intensive investigations of this disease and the search for healing methods, the contemporary theories of etiology and pathogenesis do not provide sufficient evaluation of pathological changes that occur in the femoral head. Consequently, at the current state of our knowledge the most effective ANFH therapy is a surgical intervention.

The methods of ANFH surgery can be divided into three main groups (Mikhailova and Malova, 1982; Tankut, 1966). The most radical surgeries are involved by arthroplasty of the hip joint. It should be noted that until now the necessity for such surgeries at early stages of ANFH has been beyond any doubt as wel as on patients of age $30 \div 50$. Other group of operations consists of the organ-saving ones (arthroplastic and intertrochanteric osteotomy surgeries). Unfortunately, they cannot provide positive long-time results. Since after the surgery the leg cannot be subject to any load for very a long time ($6 \div 8$ months). Besides, in this period the relevant system becomes involved in a pathological process. In addition, performing of the considered surgeries is not always justified from the biomechanical point of view, particularly in view of stiffness and strength reliability of bone. Despite of existence of a number of important and interesting theoretical and experimental studies devoted to this problem (Brown et al., 1978; Jemioło and Telega, 1998; Turner and Cowin, 1988; Miteleva, 1988), the solution to both theoretical and practical problems requires certain data on mechanical properties of bone damaged by the disease. It should be pointed out that the ANFH pathological process mostly damages the cancellous bone tissue, mechanical characteristics (particularly the rigidity characteristics) of which remain poorly investigated in pathological conditions.

The aim of this work is to investigate the stiffness properties of bone tissue of femoral head both in the state of ANFH and in the normal state. Moreover we shall study its strength non-homogeneity.

2. Materials and methods

In the process of solution and particularly the selection of operation method the mechanical characteristics of bone tissue specimen (primarily cut out along the physiological loading direction) are of interest. When the bone properties in section are being investigated it is appropriate to employ the methods used in soil mechanics. These methods are based mostly on penetration of different indentors into the substrate. They allow one to obtain easily the rigidity characteristics and also to estimate the non-homogeneity of its contact strength (Krasovsky and Loskutov, 1996; Loskutov et al., 1993, 1995).

Two series of tests have been performed: in the first one healthy femoral heads were examined, while in the second series the heads affected by aseptic necrosis were investigated.

The first series of tests have been performed on 5 samples with no pathological changes. The samples were taken from human cadavers. The cause of death was a trauma and the age was $30 \div 55$. The time since death did not exceed 12 hours.

The bone stiffness characteristics were defined on the basis of test data. The tests were performed in such a way that the steel indentor of a circular cylinder shape with a flat bottom was pressed into the bone tissue. Since aseptic necrosis mostly affects the upper part of the femoral head the investigations have been limited to this region. Moreover, for the formulated problem it suffices to investigate the processes only along the radius connecting the tip of the head with its centre (Fig.1). Such a direction approximately coincides with the direction of the maximum physiological load. The properties of the subchondral stratum and spongy tissue of four subsequent parallel cross-sections (perpendicular to the investigated direction) have been studied. The indentor penetrated the subchondral stratum at the tip of the femoral head sphere in the direction perpendicular to the tangential plane (with respect to the investigated point). The penetration into the spongy tissue was done only at the points of such projection onto the cross-section in the same direction, i.e. perpendicularly to the cross-sections (Fig.1; 1 – direction of the indentor penetration; 2 – measuring points). The cuttings have been made every 5 mm. The last cutting was made at the level of the *great circle* of the bone head.

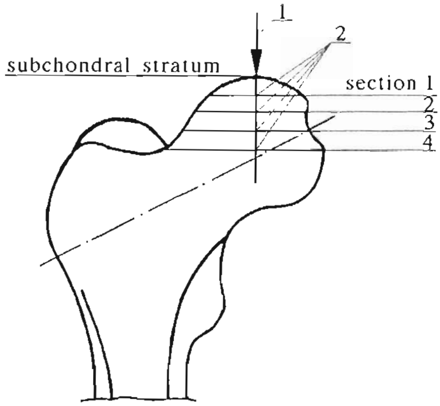

Fig. 1. The region of investigation

The indentor diameter D was equal to 2 mm. All experiments have been performed on a specially designed stand (Fig.2). The main part of this device is a clock-type displacement indicator. The load F was carried by the indentor through the stock of rigidly fixed indicator which was also used to measure the depth of indentor penetration W into the bone tissue. The accuracy of measurements was $2\,\mu$m. To obtain such an accuracy, after the reinforcement the femoral head was fixed with a gypsum blend in a disposable cage up to the level of the upper head area.

The tests were performed in the following way. For each level of gradually increasing load F the depths of full W_g and permanent (residual) W_p penetrations of the indentor into the tissue were defined. In all the tests the load was increased up to the value of $F = 40$ N. The test scheme is presented in Fig.3. The results were assumed as average values of repeated tests.

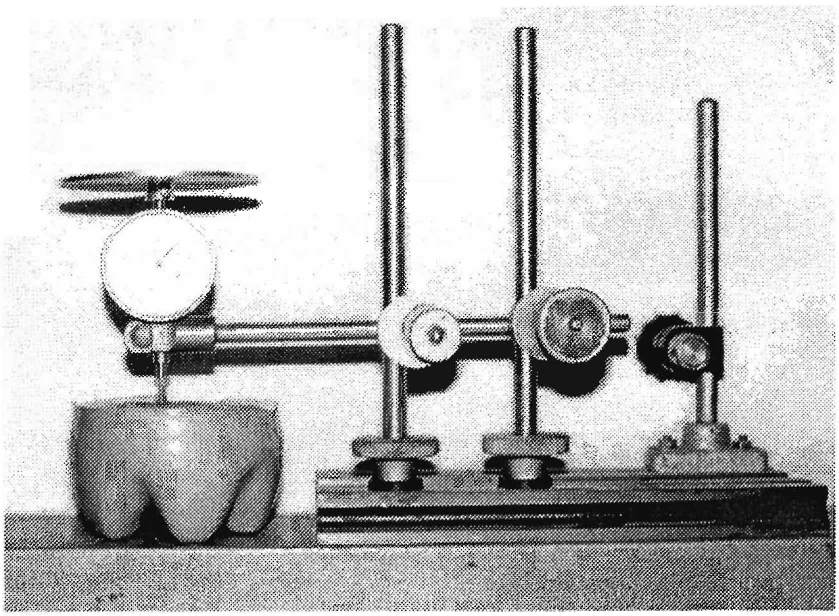

Fig. 2. General view of the test apparatus

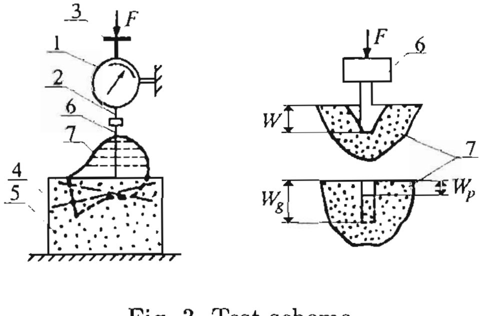

Fig. 3. Test scheme

Surgically removed femoral heads with aseptic necrosis have also been investigated using a similar technique. In these tests the authors investigated the spongy tissue stiffness only. The results were estimated and analysed not by the average values but by the values obtained for each sample individually.

3. Results of the investigation and discussion

The main result of both series of tests was determination of the relationships $F - W_g$ and $F - W_p$ that became the basis for defining the stiffness characteristics. They also allowed us to estimate the strength non-homogeneity of the subchondral stratum and spongy tissue of both the healthy femoral head as well as of the one damaged by aseptic necrosis. We have observed that purely elastic deformations were obtained only for the subchondral stratum and for the first cross-section of the healthy bone, besides it is valid only for low values of the load. On account of this the mechanical characteristics corresponding to the elasticity limit were defined neither for subchondral stratum nor for the tissue in the cross-sections.

3.1. Healthy femoral head properties

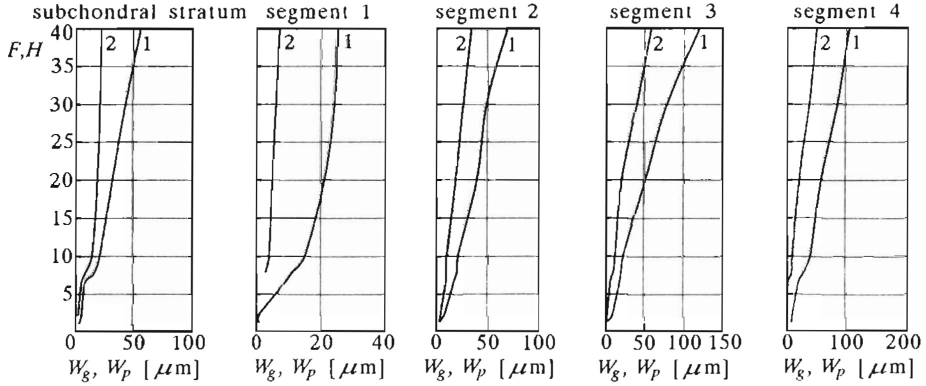

Fig. 4. Typical relationships $F - W_g$ and $F - W_p$ for the subchondral stratum and four subsequent segments of healthy femoral head

Typical relationships $F - W_g$ and $F - W_p$ for the subchondral stratum and four subsequent segments obtained for the healthy heads are shown in Fig.4. The average values of the same relationships evaluated on the basis of five tests are shown in Fig.5. In these figures the relationships $F - W_g$ and $F - W_p$ are marked with 1 and 2, respectively. To estimate visually the non-homogeneity of properties of the subchondral stratum and four cuttings the average values of the relationships $F - W_g$ and $F - W_p$ were gathered in Fig.6a and Fig.6b, respectively.

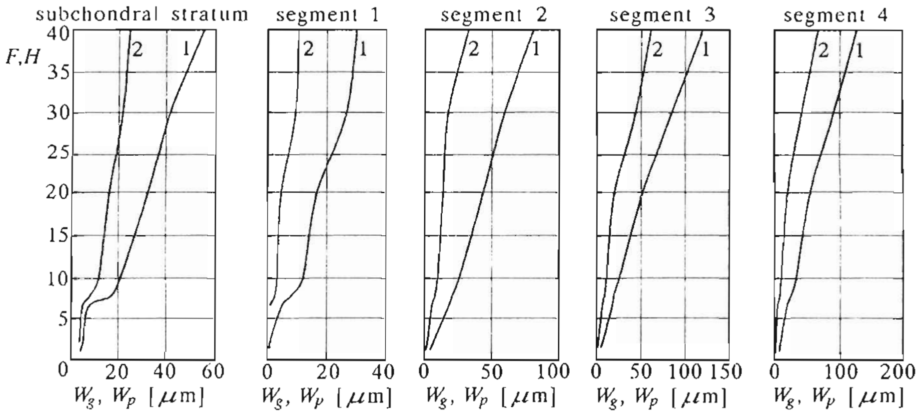

Fig. 5. Relationships $F - W_g$ and $F - W_p$ for the subchondral stratum and four subsequent segments of the healthy femoral head. Average values on the basis of 5 tests

It is reasonable to start the analysis of the obtained data from the spongy tissue. The relationships $F - W_g$ and $F - W_p$ for all segments, excluding the first one, are found to be close to the linear function. It should be pointed out that in these segments the best approximation for $F - W_g$ is the linear relationship; however, the relationship $F - W_p$ is slightly non-linear. In the first segment both relationships exhibit strong non-linearity while the relationship $F - W_p$ is close to the linear function, for $F - W_g$ it is sufficient to assume a piecewise linear approximation with three terms. Consequently, one can assume that the modulus of total deformation E_g (elastic and inelastic) represent a stiffness characteristic of the bone tissue. At the same time the elastic modulus E_e is also defined. The moduli E_g and E_e are given by

$$E_g = \frac{F(1-\nu^2)}{DW_g} \qquad E_e = \frac{F(1-\nu^2)}{D(W_g - W_p)} \tag{3.1}$$

where ν is the Poisson ratio assumed to be equal to $\nu = 0.2$. The values of E_g and E_e were calculated for all cuttings of the sample. Using the method of least squares linear approximations for $F - W_g$ and $F - W_p$ were obtained. In the first segment a three-member relationship for E_g was

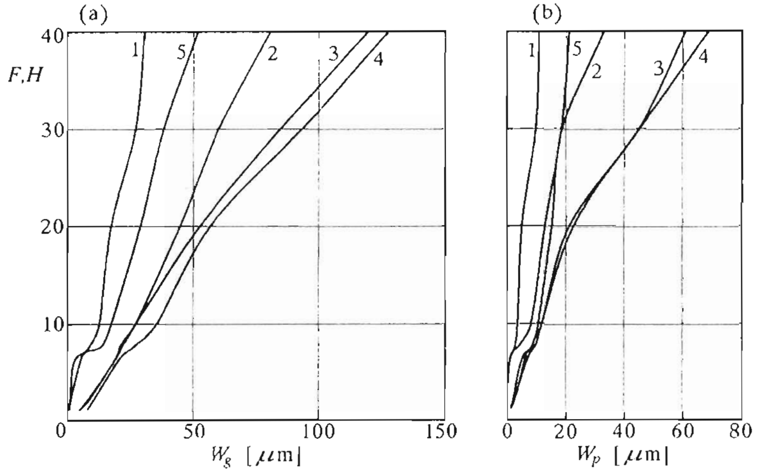

Fig. 6. The relationships: (a) $F - W_g$ and (b) $F - W_p$ for the subchondral stratum and four subsequent segments of healthy femoral head. Average values on the basis of 5 tests

constructed. In the second and third segments the values of tangential moduli of total deformation E_{g2} and E_{g3}, respectively, were defined. The following loads acting on the indentor correspond to the second and third segments: $F_2 = 6.47\,\mathrm{N}$ and $F_3 = 10\,\mathrm{N}$.

Using the data obtained for each cutting the general statistical characteristics of E_g and E_e: average values of E_g and E_e, confidence intervals for these parameters with the probability 0.95 and variation coefficients V_g and V_e, which determine the variation ranges for the parameters considered and calculated with the same probability. The variation coefficients were obtained using the following formula

$$V_i = 2\frac{S_i}{E_i} \cdot 100\% \tag{3.2}$$

where S_i is the average quadratic deviation of E_i, $i = e, g$. The results of calculations are presented in Table 1. For the first cutting the value of E_g in Table 1 is given only for the first segment of the relationship $F - W_g$. The overall stiffnes characteristics of cancellous tissue in this segment are given in Table 2.

Table 1. The stiffness characteristics of spongy tissue of the healthy femoral head and their statistical properties

	E_g [MPa]	V_g [%]	E_e [MPa]	V_e [%]	E_g/E_e
Segment 1	647 ± 29.2	7.40	827 ± 183	35.9	0.782
Segment 2	210 ± 62.3	48.0	339 ± 191	90.7	0.619
Segment 3	164 ± 10.0	9.80	316 ± 29.0	14.8	0.520
Segment 4	154 ± 11.5	12.0	297 ± 8.90	4.80	0.518

Despite of the fact that the parameters defining the strength of the bone tissue were not established in this investigation, one can estimate implicitly the change in the strength of this tissue along the height of the femoral head by the ratio between modulus of total deformation and elastic deformation ratio (see the last column of Table 1). Reduction in this ratio obviously corresponds to weakening of strength properties of the bone. As it is seen from Table 1 the mechanical characteristics of healthy heads (except for the segment 2) are quite stable and reveal rather high rigidity. The maximum value of rigidity (E_g = 647 MPa) considerably exceeds the corresponding parameters for the cancellous bone tissue of the distal cross-section. Reduction in the stiffness and strength parameters from the periphery to the centre of the head is clearly seen. We observe that the stiffness properties decrease considerably faster than the strength ones. For instance, the modulus of total deformation of the bone, which undergoes most significant changes, decreases to the centre of the head 4.2 times whilst the strength changes do not exceed 35%. These changes are clearly seen in Fig.7a. One can visually analyse the values of E_g and E_e presented in Table 1.

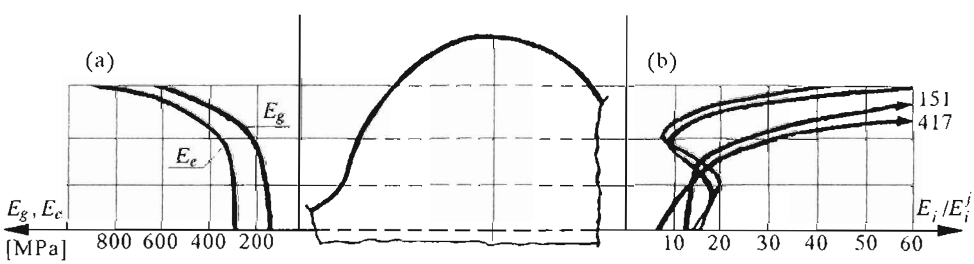

Fig. 7. Changes in the stiffness characteristics of cancellous bone tissue along the height

The most considerable change in the stiffness characteristics of the bone occurs when moving from the cross-section 1 to the cross-section 2. Then E_g and E_e decrease 3.1 and 2.43 times, respectively. It should be noted that it is the gradient of these characteristics that causes considerable increase in the deviation of E_g and E_e in the segment 2, where the variation coefficients are several times higher when compared with the other cuttings and become equal to $V_g = 48\%$, $V_e = 91\%$ (see Table 1). The most significant reduction in the strength of the bone also occurs in this zone (by 33%). In the central zone the strength of the tissue does not change considerably.

When looking at the relationships $F - W_g$ and $F - W_e$ obtained for the subchondral stratum, it should be pointed out that they reveal relatively high qualitative stability and that their behaviour under load is quite complicated.

As we already know the relationship $F-W_g$ has three-terms character that practically allows one to use the linear approximation in each segment. Unlike the cancellous bone tissue, the second segment of the relationship $F - W_g$ for the subchondral tissue subject to the load $F = 7.73\,\mathrm{N}$ is a horizontal straight line similar to the yield part of the stress diagram for a low-carbon steel.

Prior to numerical estimation of the strength of subchondral stratum it is worth while to note that penetration of indentor into the cancellous bone tissue allows one to obtain the stiffness characteristics of this tissue through the moduli of total and elastic deformations. The same kind of penetration into the subchondral stratum yields the stiffness characteristics not for the subchondral stratum tissue but for the object of a biostructure consisting of thin shell of the subchondral stratum in the aggregate, i.e. the cancellous bone tissue. Thus the indentor displacement under the load consists of bending deformation of the shell with the aggregate and deformation of the indentor penetrating into the subchondral stratum tissue. Nevertheless, despite of a considerable difference in the definition, the authors used the same parameters and ratios as for the cancellous bone tissue. The values of the rigidity parameters on the first, second and third segments are assigned as E_{g1}, E_{g2} and E_{g3}, respectively. The general linear approximation was constructed for the $F-W_p$ relationship.

Table 2. Stiffness characteristics of subchondral stratum and cancellous bone tissue of healthy femoral head and their statistical properties

	E_{g1} [MPa]	V_{g1} [%]	E_{g2} [MPa]	V_{g2} [%]
Subchondral stratum	943 ± 434	74.2	0	0
Segment 1	647 ± 29.2	7.40	168 ± 31.0	29.3
	E_{g3} [MPa]	V_{g3} [%]	E_e [MPa]	V_e [%]
Subchondral stratum	489 ± 98.1	32.3	827 ± 23.8	4.37
Segment 1	831 ± 330	64.0	877 ± 184	35.9

The main statistical parameters for E_{gi} and E_e are: the average values of

E_{gi} and E_e; the confidence intervals of these values with the probability 0.95; variation coefficients V_g and V_e which are given in Table 2. The tangential modulus of the total deformation E_{gi} and modulus of elasticity E_e of the cancellous bone tissue in the first Section 2 are also presented in Table 2.

The analysis of relationships $F - W_g$ and $F - W_e$ carried out for the subchondral stratum and the cancellous bone tissue in the first segment together with the data shown in Table 2 leads to the following conclusions. The main component determining the stiffness of the subchondral stratum (as a biostructure *subchondral stratum plus cancellous bone tissue* composition) is the cancellous bone tissue. The subchondral stratum, reinforcing a cancellous bone, increases its rigidity at initial stages of loading (the first segment). However, this increase is insignificant (column 1 of Table 2) and shows only the tendency (statistically unproved). It means that the subchondral stratum reveals low bending rigidity. We also observe considerable difference in E_{g1} for the subchondral stratum in comparison with the adjacent cancellous bone tissue of the cutting 1. This fact contradicts the generally accepted concept of subchondral stratum according to which its main role is to stabilize the stiffness properties of the joint and bone. Our conclusions, however, are drawn from the limited number of tests.

Higher stiffness of the subchondral stratum (in comparison with the cancellous bone tissue of Section 1 located underneath) is found only for the first segment $F < 7.73\,\mathrm{N}$. For $F > 7.73N$ (in the second and third segments), and globally (because of large deformations in the second segment) the rigidity of subchondral stratum was lower than the rigidity of the adjacent cancellous bone tissue. It means that the subchondral stratum tissues reveal low stiffness characteristics in the direction normal to this stratum. We note that the investigations conducted do not clarify sufficiently the meaning of the horizontal part of the relationship $F - W_g$ as well as the way it might occur in a real process of loading. One may assume that this straight line can be physically obtained when the contact stresses under the bottom of indentor reach their limit values for the subchondral stratum tissue. Such a line might be needed by *preventive mechanisms of organism* to reduce the stresses in the subchondral stratum tissue when the load increases from the stationary (regular) magnitudes carried by the joint. All these effects, found in subchondral stratum behaviour, show the necessity for further investigations into its biomechanical properties. The major result of these studies is clarification of the role of the subchondral stratum in providing the local rigidity of biostructure of the femoral head. As it was stated earlier, the tissue of this stratum reveals low stiffness. Therefore even the slightest localized decrease in the rigidity of cancellous bone tissue, located underneath the subchondral stratum, can lead to decrease in the stiffness of the femoral head itself. In other words, the subchondral stratum is not capable of compensation for the loss of rigidity of the adjacent cancellous bone tissue caused by disease.

Concluding the considerations concerning healthy samples of femoral head, we observe that because of considerable anisotropy of cancellous bone tissue of femoral head all data presented above are adequate only for one direction close to the direction of application of the maximum physiological load.

3.2. Properties of the femoral head damaged by aseptic necrosis

The results obtained from the tests of series 2 considerably differ from the corresponding results for the healthy femoral head. The experimental relationships $F - W_g$ (see Fig.1) and $F - W_p$ (Fig.3) for the four subsequent segments of the femoral head at the second and third stage of ANFH are given in Fig.8 and Fig.9, respectively.

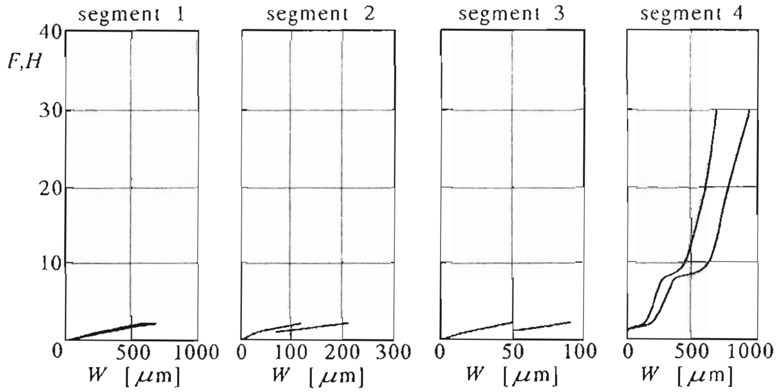

Fig. 8. The relationships $F - W_g$ and $F - W_p$ for 4 subsequent segments of the femoral head at the second stage of aseptic necrosis

When the bone at the second stage of ANFH was investigated in the segments $1 \div 3$ for the load values slightly exceeding $2\,\mathrm{N}$ (5% of the control limit value $F = 40\,\mathrm{N}$) one can observe the total destruction of the bone tissue under the indentor in a form of collapse (the indentor completely submerged into the tissue).

In the centre of the femoral head (segment 4) the bone tissue appear to be more dense and, consequently, stronger. Its failure occured at the load level $F = 30\,\mathrm{N}$, which is, however, also lower than the control load value. For all segments the quantitative parameters of the obtained relationships $F - W_g$

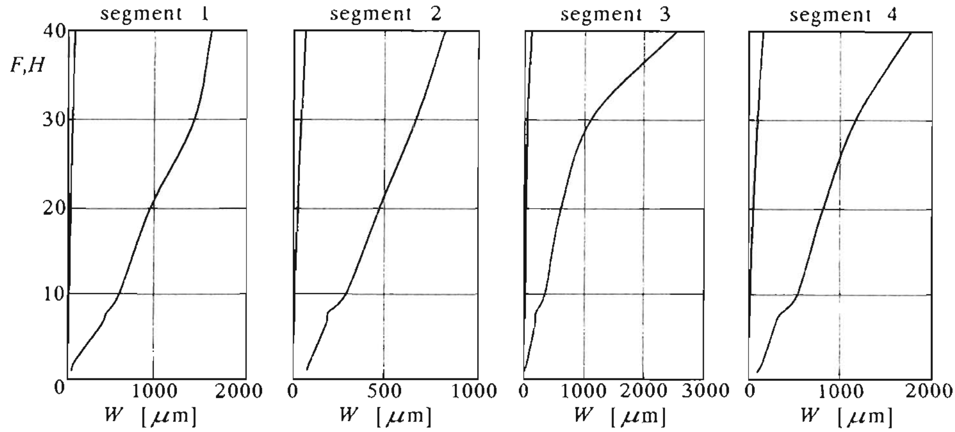

Fig. 9. The relationships $F - W_g$ and $F - W_p$ for 4 subsequent segments of the femoral head at the third stage of aseptic necrosis

and $F - W_p$ significantly differed from the normal values. Significant reduction in the bone rigidity is observed. At the third stage of disease the bone tissue in all segments carried the control load. The relationships $F - W_g$ and $F - W_p$ were close to the ones obtained for the healthy samples but quantitatively there is a significant difference.

Table 3. Characteristics of the rigidity of the cancellous bone tissue damaged by aseptic necrosis

	E_{gs} [MPa]	E_g/E_{gs}	E_{es} [MPa]	E_e/E_{es}	E_{gt} [MPa]	E_g/E_{gt}	E_{et} [MPa]	E_e/E_{et}
Seg. 1	1.55	417	5.48	151	10.9	59.4	19.2	43.1
Seg. 2	5.33	39.4	11.7	29.0	22.1	9.52	44.6	7.60
Seg. 3	12.0	13.7	24.0	13.2	8.93	18.4	16.7	19.0
Seg. 4	11.5	13.4	43.6	6.81	10.7	14.4	19.8	15.0

On the basis of the relationships $F - W_g$ and $F - W_p$, similarly as for the healthy samples, the moduli of total and elastic deformations of the cancellous bone tissue damaged by aseptic necrosis have been found. The results are presented in Table 3. The characteristics of the rigidity of the bone at the second and third stages of disease are marked with subscripts s and t, respectively. The ratio between stiffness parameters of healthy and pathological samples in each cutting are also given in Table 3. They allow one to estimate the reduction of the bone rigidity caused by the disease (these data are represented in Fig.7b).

From Table 3 it is seen that at the second stage of the disease the maximum reduction of the bone rigidity (more than 400 times) occurs on the periphery (cross-section 1) while the minimum (approximately ten times less than the maximum) occurs at the centre of the femoral head (cross-sections 3,4). The gradient of the stiffness factor along the height of the femoral head considerably changes: the maximum rigidity of the cancellous bone tissue occurs at the centre of the femoral head, whilst the minimum – in the subchondral stratum.

At the third stage of the disease the maximum reduction of the stiffness also occurs in the cutting 1, however, the value of this reduction is smaller (approximately 60 times). The maximum rigidity of the bone in this case was found in the segment 2. Quantitatively it is only twice of the rigidity of the tissue in other cuttings, where the stiffness was practically the same, i.e. close to the rigidity of the cancellous bone in the central zone of the femoral head at the second stage of the disease.

3.3. Conclusions

- The cancellous bone tissue of the healthy femoral head has sufficiently high and stable stiffness which reduces from the tip of the femoral head towards its centre. The modulus of the total deformation determining the bone rigidity changes from 647 to 154 MPa. The character of the strength change is the same, however, its reduction does not exceed 35%.

- The pathological changes in the cancellous bone tissue caused by ANFH both at the first and second stages of the disease lead to considerable (minimum ten times) reduction of its strength and rigidity in the upper half of the femoral head sphere. The maximum reduction of the strength and stiffness (more than 400 times) occurs at the second stage of the disease in the peripheral area (located under the subchondral stratum).

- Healthy subchondral stratum tissue has comparatively low stiffness, therefore the healthy subchondral stratum cannot compensate even for an insignificant local stiffness loss of adjacent cancellous bone tissue because of the disease.

- Significant reduction of the stiffness and strength properties of the bone tissue make it doubtful whether at the second and third stages of ANFH surgical interventions such as arthroplastic and intertrochanteric osteotomy are purposeful. Indeed, in such a case it is rather necessary to insert partial or total endoprosthesis of the hip joint. This conclusion also pertains to relatively young patients.

Ackonowledgement

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Charakterystyki wytrzymałościowe zdrowej główki kości udowej i główki uszkodzonej przez martwicę

Streszczenie

W pracy zbadano sztywność tkanki kostnej zdrowej główki kości udowej oraz wykazano zmiany charakterystyki w główce kości udowej zdegenerowanej przez martwicę.

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