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## **STUDY OF THE STRESS-DEFORMED STATE OF THE HIP JOINT MODEL IN CHILDREN UNDER THE CONDITIONS OF DYSPLASIA AND CONSERVATIVE TREATMENT**

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In this work, a comparative study of the stress-strain state of the elements of the hip joint in children in normal and in the case of its dysplastic changes in the application of the technique of "trampling" used for conservative treatment of hip dysplasia. To solve this goal, several mathematical models of the child's hip joint were built using the finite element method. In the process of constructing the calculation model, the geometric model of the pelvis-thigh was taken as a basis, which is based on the method of creating a model of geometric sections obtained from tomographic images. As a result of the conducted mathematical research significant changes in the nature of the stress-strain state in normal and dysplastic hip joint using the technique of "trampling" in comparison with previously obtained data for single-support standing, which, in our opinion, may be one of the significant factors joint in the process of conservative treatment. The obtained data should contribute to the definition and optimization of methods of additional mechanical stimulation of the components of the hip joint for its normal development during treatment.

**Key words:** hip joint, dysplasia, child, biomechanics, acetabulum.

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## **ДОСЛІДЖЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ МОДЕЛІ КУЛЬШОВОГО СУГЛОБА У ДІТЕЙ В УМОВАХ ДИСПЛАЗІЇ ТА КОНСЕРВАТИВНОГО ЛІКУВАННЯ**

В даній роботі проведено порівняльне дослідження напружено-деформованого стану елементів кульшового суглоба у дітей в нормі та у випадку його диспластичних змін в умовах застосування методики «топтання», що застосовується для консервативного лікування дисплазії кульшових суглобів. Для вирішення поставленої мети були побудовані декілька математичних моделей дитячого кульшового суглобу за допомогою методу скінчених елементів. У процесі побудови розрахункової моделі за основу була взята геометрична модель таз-стегно, в основу якої покладено методику створення моделі по геометричних перетинах, отриманих з томографічних знімків. В результаті проведеного математичного дослідження встановлено значні зміни характеру напружено-деформованого стану в нормальному та диспластичному кульшовому суглобі при застосуванні методики «топтання» в порівнянні з раніше отриманими даними для одноопорного стояння, що, на нашу думку, може бути одним із суттєвих факторів дорозвитку диспластичного кульшового суглобу в процесі консервативного лікування. Отримані дані мають сприяти визначенню та оптимізації методів додаткової механічної стимуляції компонентів кульшового суглоба для його нормального дорозвитку в процесі лікування.

**Ключові слова:** кульшовий суглоб, дисплазія, дитина, біомеханіка, кульшова западина.

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This work is a logical continuation of many theoretical and experimental-biomechanical studies, which show that bone tissue is a mobile and plastic material, and in particular, changes in mechanical loads affect the bone structure by changing its mass and architecture. Thus, the law of J. Wolf formulated in the 19th century states that the bone of a healthy person adapts to the constant periodic loads to which it is exposed. That is, if the load on any bone increases, the bone is rebuilt in such a way as to better withstand the load [5, 8, 10].

According to previous studies, bone growth and/or bone remodeling is stimulated by local cyclic mechanical elastic action (deformation) on the bone. Reconstruction of bone in accordance with the load is carried out by mechanotransduction – the process by which forces and other mechanical signals are converted into cellular signals. It is proved that the effects of cellular reorganization of bone tissue depend on the duration, amplitude and strength of the load, and also the influence of cyclic loads on the stimulation of bone formation was revealed [6, 8].

Some studies have shown that the amount of force (e.g., body weight) is an important factor influencing the skeleton, but other physical characteristics of its action are important, such as the speed of force action. Slow application of force for a few seconds is not perceived by bone cells as a stimulus, but they are sensitive to very rapid forces (such as jumps or blows), even less than the amount of effort applied [8].

A classic example of bone remodeling is the gradual development of dystrophic changes in the elements of the hip joint (HJ) against the background of dysplastic coxarthrosis [1, 2, 6]. In this case, certain anatomical deviations in the structure of the HJ (underdevelopment and obliqueness of the acetabulum (HJA), multiplanar deformities of the proximal femur (PF) in the form of pathologically increased anterior torsion angle (ATA) and/or cervical-diaphyseal angle (angle of inclination) valgus deformation), in the case of their long existence and constant impact, lead to local overload at the points of contact of the joint components and the emergence of osteosclerosis zones, and then the progression of dystrophic changes in bone and cartilage [4, 6].

The same phenomena are observed as a result of studying other segments, in particular knee, and shoulder joints. Similar dystrophic changes in these segments also occur due to abnormal anatomical structure or as a result of trauma – fractures, damage to the joint ligaments, and so on.

It is logical to assume that in the case of the same situation (dysplastic changes in the HJ), under conditions of prolonged exposure to physiological loads that imitate walking or jumping (in particular, the so-called “trampling” method), but directed towards the center of the femoral head (FH), it is possible to cause a certain rearrangement and transformation of bone tissue HJA and PF, which will remodel the components of HJ in the direction of development (increase in sphericity of HJA, decrease cervical-diaphyseal angle CDA and AA), and therefore will decrease dysplastic changes in HJ [3]. Previously obtained clinical results of the method of “trampling” indicate its positive effect on the development of HJ, but these observations require biomechanical substantiation and confirmation, including using the finite element method (FEM) with the study of stress-strain state (SSS) in the elements of the joint.

**The purpose** of the study was to perform a comparative study of the stress-strain state of the hip joint elements in children in the case of physiological loads (walking – “trampling”) in normal and dysplastic changes in the acetabulum and proximal femur.

**Materials and methods.** To solve this goal, several mathematical models of children's HJ were built using sociomedical assessment (SMA). Construction of these models and calculations were performed in SolidWorks [7].

As in the previous work in the process of building the calculation model was based on the geometric model of the pelvis-thigh, developed in the laboratory of biomechanics SI “Sitenko IPHS NAMS”, which is based on the method of creating a model of geometric sections of HJ elements obtained from tomographic images, and changes were made to the constructed model, according to previous studies on the features of early childhood HJ.

Taking into account the above changes, several variants of the HJ calculation models were built:

1. Model of normal HJ with cervical-diaphyseal angle, which was  $130^\circ$ , antetorsion angle -  $20^\circ$ , normal acetabulum (acetabular index -  $25^\circ$ ) – stress-strain state (SSS) elements of HJ was determined under the conditions of “trampling” in the position of hip abduction at  $50^\circ$ , which provides the centering of the femoral head (CFH);

1. Model of dysplastic HJ with cervical-diaphyseal angle, which was  $130^\circ$ , antetorsion angle -  $20^\circ$  and acetabular index  $60^\circ$  – determination of SSS of HJ elements under the conditions of “trampling” in the position of hip abduction by  $50^\circ$ ;

2. Model of dysplastic HJ with cervical-diaphyseal angle, which was  $130^\circ$ , antetorsion angle of  $40^\circ$  and acetabular index of  $60^\circ$  – determination of SSS of HJ elements under conditions of “trampling” in the position of hip abduction by  $50^\circ$ ;

3. Model of dysplastic HJ with cervical-diaphyseal angle, which was  $130^\circ$ , antetorsion angle of  $40^\circ$  and acetabular index of  $60^\circ$  – determination of SSS of HJ elements under conditions of “trampling” in the position of hip abduction by  $50^\circ$  and internal rotation by  $20^\circ$ , which provides “improved” FBH centering.

**Properties of materials.** In this study, as in the previous one, the material was considered homogeneous and isotropic, and the choice of properties of bone structures was based on data that are most common in the literature [9]. The following characteristics of the materials were used: E - modulus of elasticity (Young's modulus) and  $\nu$  – Poisson's ratio, which are presented in table. 1.

**Load scheme.** In this paper, we considered one variant of the load – the so-called “trampling”, when the load of 100 N falls on the lower plane of the left knee joint, and the left pelvis is fixed in the sacroiliac joint and pubic symphysis. However, the obtained indices were also compared to the models that determined the state of SSS of the HJ under the conditions of single-support standing, which we presented in the previous work. It should be noted that in the process of “trampling” the real load will be higher,

taking into account the dynamic coefficient, which depends on the height of trampling. The calculation of this coefficient taking into account the heterogeneous properties of materials, the complex geometry of the model, deformation of the support, the inertia calculation is not a trivial task.

Table 1

**Mechanical characteristics of the materials used**

Tissue	E (МПа)	$\nu$
Cortical bone	12240	0.3
Spongy	380	0.3
Cartilage	10.5	0.49
Growth zone	5	0.45

However, since the problem is solved in a linear setting, the increase in load will lead to a proportional increase in stress, and the nature of the SSS distribution will not change. In this regard, we considered it possible to perform calculations under static load to determine the nature of the SSS distribution of different models. As an assessment of the stress state, Mises stresses were selected as the most informative type of the general stress state. In the course of our study in the text, all numbers are rounded to one decimal place.

Initially, the analysis of SSS elements of the HJ during the procedure of “trampling” in the normal anatomical structure of the HJ elements was performed. These data are necessary for further comparative analysis in the case of different variants in the model of dysplastic HJ in children.

*Analysis of the stress-strain state of the components of the hip joint in children in the process of “trampling” under the normal structure of the HJ.*

The analysis of the SSS model of the normal HJ in the process of “trampling” showed that the nature of the stress distribution has changed in comparison with the single-support standing. The most intense is the lower part of the neck of the HJ, as well as the area of the sacroiliac joint and the lower branch of the pubic bone. This is due to the redistribution of effort and movement constraints imposed on this model. In the acetabulum, zones with high stress are observed in the anterior-upper and posterior sections of the edge of the depression, as well as in its center (front, upper and rear sections for the model of single-support standing).

Thus, in the anterior-upper region, the Mises stresses reach 0.7 MPa, and at the posterior edge - 1 MPa, in the center of the acetabulum the level of the stress state is equal to 0.5 MPa. The nature of the distribution of the stress state along the thickness of the bone of the acetabulum in the process of “trampling” also changed in comparison with the single-support standing. More intense is the central-medial section of the acetabulum (upper and upper-lateral sections for single-support standing).

The analysis of the SSS model of the normal HJ in the process of “trampling” showed that the nature of the stress distribution has changed in comparison with the single-support standing. The most intense is the lower part of the HJ neck, as well as the area of the sacroiliac joint and the lower branch of the pubic bone. This is due to the redistribution of effort and movement constraints imposed on this model. In the acetabulum, zones with high stress are observed in the anterior-upper and posterior sections of the edge of the acetabulum, as well as in its center (front, upper and rear sections for the model of single-support standing). Thus, in the anterior-upper region, the Mises stresses reach 0.7 MPa, and at the posterior edge – 1 MPa, in the center of acetabulum the level of the stress state is equal to 0.5 MPa. The nature of the stress state distribution along the thickness of the HJ bone in the process of “trampling” also changed in comparison with the single-support standing. More intense is the central-medial section of the acetabulum (upper and upper-lateral section for single-support standing).

Based on the calculations of this HJ model, the following results were obtained:

- in the process of “trampling” the normal HJ changes the nature of the SSS distribution in acetabulum in comparison with the single-support stand;

- the most intense areas there were in the calculation HJ model were the area of the femoral neck and sacroiliac joint (for single-support standing it is the area of the neck and the medial side of the PF). This redistribution of SSS is explained by changes in the geometry of the model (the mutual location of the pelvis and thighs) and changes in the model of load and restrictions;

In acetabulum the front, front-upper and rear edges, as well as the central part are more intense, i.e. increases almost along the entire depression, except for the lower part. In this case, the level of stress in these areas differs within (below in the central part); the front, front-upper and rear edges, as well as the central part are more intense, i.e. increases almost along the entire depression, except for the lower part. In this case, the level of stress in these areas differs within 20 % (below in the central part); the thickness of the bone tissue acetabulum, more intense is the central medial part of it.

*Analysis of the stress-strain state of the HJ components in children in the process of “trampling” in the case of an antetorsion angle of 20° and dysplastic acetabulum with an acetabular index of 60°.*

Analysis of SSS of this model of HJ in the process of “trampling” showed that the most intense is, as for the model of HJ in the norm, the lower part of the femoral neck, as well as the sacroiliac joint and lower branch of the pubic bone (fig. 1b). In the acetabulum, the nature of the SSS distribution compared to the norm has changed: the front and upper edges of the acetabulum are more intense, and at the rear edge the level of stress has become lower than for the normal model. Thus, in the anterior region of the short circuit, the Mises stresses reach 0.8 MPa (0.7 MPa for the normal model) and 0.3 MPa at the rear edge (0.7 MPa for the normal model). At the upper edge of the acetabulum, the stress level increased to 0.5 MPa (0.2 MPa for the normal model). In the center of the acetabulum, the level of stress, as for the normal model, is equal to 0.5 MPa (fig. 2b). The nature of the stress state distribution the along the thickness of the acetabulum bone in the process of trampling for the model with an acetabular index of 60° did not change in comparison with the model in the norm. The central medial section of the acetabulum is more intense.

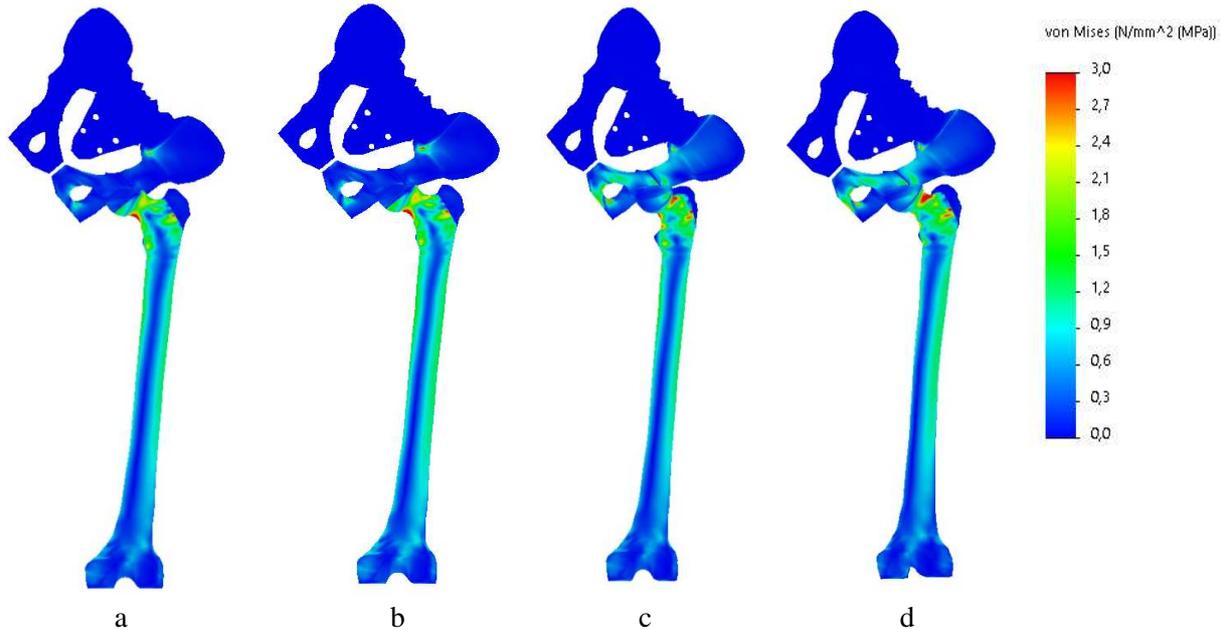


Fig. 1 Mises stress - a complete model of the HJ: a) the norm; b) acetabular index 60°; c) acetabular index 60° + antetorsia of the femur 40°; d) acetabular index 60° + antetorsia of the femur 40° + internal rotation by 20°.

- Based on the calculations of this model of the HJ, the following results were obtained:
- in the conditions of acetabulum dysplasia (acetabular index 60°) the most intense areas, as for the model, are normally the area of the femoral neck and sacroiliac joint, but the degree of SSS is higher in the conditions of dysplasia than normal;
- the nature of the SSS distribution in comparison with the norm has changed in the acetabulum. Its front and upper edges are more intense, and at the rear edge the level of tension has decreased. In the central part of the acetabulum, the level of stress has not changed.

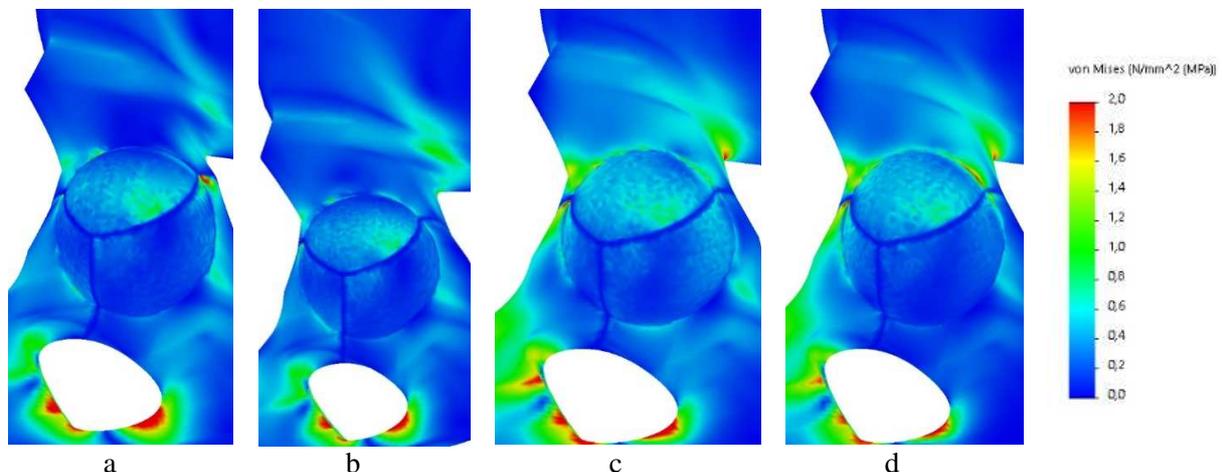


Fig. 2. Mises stress-model of the acetabulum: a) norm; b) acetabular index 60°; c) acetabular index 60° + antetorsia of the femur 40°; d) acetabular index 60° + antetorsia of the femur 40° + internal rotation by 20°.

*Analysis of the stress-strain state of the HJ components in children in the process of “trampling” in the case of an antetorsion angle of 40° and dysplastic acetabulum with an acetabular index of 60°.*

Analysis of this model SSS showed that the nature of SSS distribution has changed somewhat: it was found that in comparison with previous calculations the most intense are the lower part of the femoral neck and lower pubic bone, and in the sacroiliac joint tension decreased. In the acetabulum, the nature of the SSS distribution compared to previous calculations has also changed. The most intense is the leading edge of the acetabulum, at the upper edge the level of stress has also increased compared to previous calculations. Thus, in the anterior region of the acetabulum, the Mises stresses reach 1.1 MPa (0.7 MPa for the normal model) and 0.7 MPa at the rear edge (1 MPa for the normal model).

At the upper edge of the acetabulum, the stress level increased to 0.8 MPa (0.2 MPa for the normal model). At the center of the acetabulum, the stress level is 0.9 MPa (0.5 MPa for the normal model). The nature of the stress distribution along the bone thickness of the acetabulum in the process of trampling for the model of HJ with increased antetorsion and dysplastic acetabulum did not change in comparison with the model of normal HJ. The central medial section of the acetabulum is more intense.

- Based on the calculations of this model of the HJ, the following results were obtained:
- in the presence of acetabulum dysplasia (acetabular index 60°) and pathological antetorsion (40°) the most intense areas are the lower part of the femoral neck and the lower branch of the pubic bone;
- in the acetabulum, the nature of the SSS distribution has changed compared to the norm: the presence of excessive antetorsion in addition to the dysplasia of the acetabulum has led to a redistribution of efforts and increased stress in the front of the cavity;
- the most intense is the leading edge of the acetabulum, where the level of stress, compared to the rear of the depression, is higher by more than 40 %;
- at the rear, upper edge, as well as in the central part of the acetabulum, the level of stress has increased compared to previous calculations.

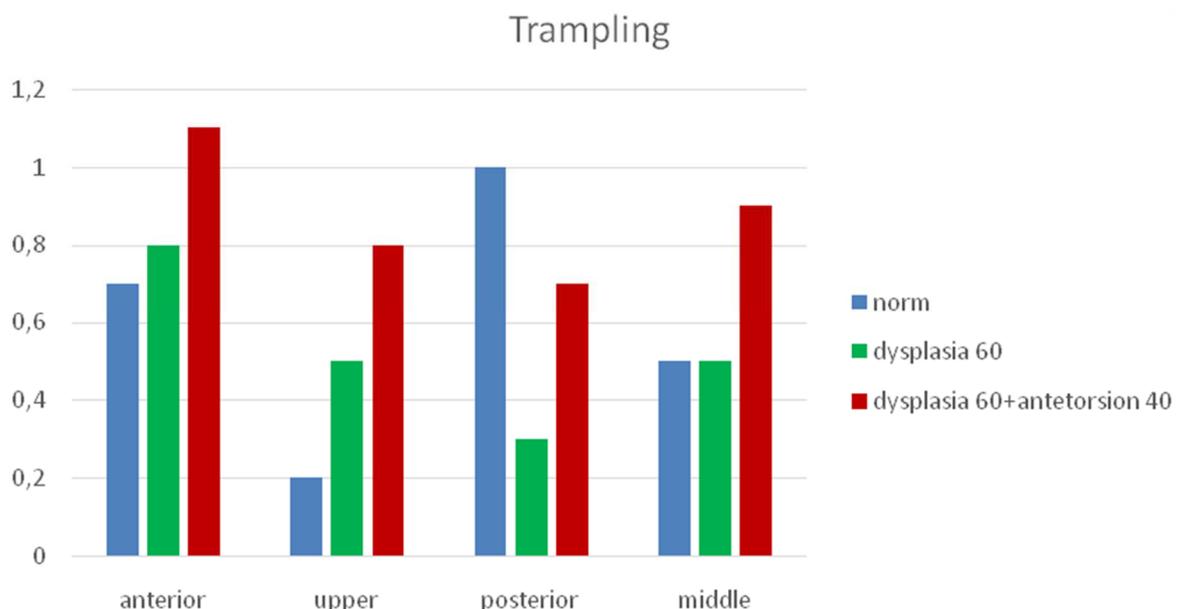


Fig. 4 The values of Mises stress in the acetabulum.

*Analysis of the stress-strain state of the HJ components in children in the process of “trampling” in the case of an antetorsion angle of 40°, dysplastic acetabulum with an acetabular index of 60° in the position of internal rotation of the thigh by 20°.*

To obtain a more uniform distribution of the stress state in the acetabulum, a model with additional internal rotation of the thigh by 20 was built. In the acetabulum, the nature of the SSS distribution compared to previous calculations has changed. The anterior-upper-posterior edge of the acetabulum became more intense. Thus, in the anterior region, the Mises stresses reach 1.5 MPa (0.7 MPa for the normal model) and 2 MPa at the rear edge (0.7 MPa for the normal model).

At the upper edge of the acetabulum, the stress level increased to 1.4 MPa (0.2 MPa for the normal model). In the center of the acetabulum, the level of stress is equal to 0.9 MPa (0.5 MPa for the normal model). The nature of the stress state distribution along the thickness of the bone of the acetabulum during trampling for the model with additional rotation has not changed compared to the model in the norm. The central medial section of the acetabulum is more intense.

- Based on the calculations of this model of the HJ , the following results were obtained:
- the use of additional internal rotation of the thigh during trampling changed the nature of the SSS distribution in the acetabulum;
- in the presence of dysplastic changes and rotation of the femur, the level of stress increases at the edge of the acetabulum;
- in the presence of acetabulum dysplasia and excessive antetorsion, additional rotation leads not only to an increase in the level of stress at the edge of the acetabulum, but also to a decrease in the difference between the level of tension of the anterior and posterior edges, respectively from 40 % (without rotation) to 20 % rotation);
- the level of stress in the central part of the acetabulum does not change.

Thus, based on data by a number of authors proving the effect of SSS distribution on bone development and shape [8, 10] and the effect of SSS deviations on articular cartilage [5, 6], the changes in SSS found in this study using the technique of “trampling” can to be one of the essential factors in the development of dysplastic hip joint in the process of conservative treatment.

### Conclusions

1. In the process of “trampling” of the normal HJ, the most intense areas in the calculation model of the HJ is the area of the femoral neck and sacroiliac joint. In acetabulum more intense are the front, front-upper and rear edge, as well as the central part, i.e. SSS increases in almost the entire depression, except the lower part, while the level of stress in these areas differs within 20 %;

2. In the process of “trampling” of the HJ in the case of an antetorsion angle of 20° and dysplastic acetabulum with an acetabular index of 60°, the following changes were detected: norm to 0.5 MPa (ie VAT increased 2.5 times), and at the rear edge the stress level decreased from 0.7 MPa for the model to normal to 0.3 MPa, in the central part of the acetabulum the stress level did not change;

3. In the case of determining the SSS in the process of “trampling” of dysplastic HJ with an antetorsion angle – 40° and acetabular index – 60°, it is found that the stress level increases significantly at the top of the edge of the acetabulum by 2.5 times, and in the center of the depression by 55 %. It should be noted that the level of stress at the rear of the edge of the short circuit is reduced by 3 times;

4. In the process of “trampling” the HJ with an antetorsion angle – 40° and acetabular index – 60° with an additional position of the internal rotation of the thigh by 20°, it is established that there is not only an increase in stress at the edge of the acetabulum, but also a difference between stress front and rear edges, respectively, reduces from 40 % (without rotation) to 20 % (with rotation). The level of stress in the central part of the acetabulum does not change.

Therefore, the stresses identified in this study, as well as the nature of their distribution in proximal femor and acetabulum, in our opinion, may be one of the significant factors in the reconstruction and development of the acetabulum in case of dysplastic changes in the elements of the hip joint, which requires further clinical verification.

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